University of Alberta

Establishment of a Vegetation Cover on Kimberlite Mine Tailings

By

Neil Burton Reid ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science

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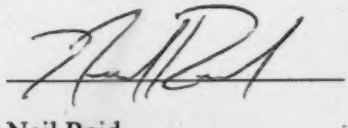

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ABSTRACT

Stabilizing processed kimberlite tailings with a vegetation cover after diamond extraction has prompted research at the Ekati Diamond Mine™ in the Canadian sub-arctic barrenlands. Laboratory testing has shown coarse texture, no organic component and a lack of available macronutrients to be the principal limitations to plant colonization. Structural improving and nutrient providing amendments were used to ameliorate these plant growth limitations thus facilitating the establishment of a permanent vegetation cover on the Ekati kimberlite tailings containment area, stabilizing the surface materials and promoting natural colonization by the surrounding tundra vegetation. Seven native grass species (*Arctagrostis latifolia*, *Calamagrostis canadensis*, *Poa glauca*, *Poa alpina*, *Deschampsia beringensis*, *Festuca rubra* and *Deschampsia caespitosa*) were used to measure amendment success. With the addition of structural improving and nutrient providing amendments, plant growth on these kimberlite tailings has significantly improved (unamended 4% cover; with amendment as high as 70% cover). The most successful amendment combinations included peat moss or papermill sludge in combination with biosolids from the mine site.

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CHAPTER I. INTRODUCTION

1.1 EKATI™ DIAMOND MINE

The discovery of diamonds in the Northwest Territories (NWT) in 1991 by Charles Fipke and Stewart Blusson resulted in the largest staking rush in Canadian history (BHP Diamonds Inc. 1994). Two years after the discovery BHP Billiton, an Australian mining company, began extensive exploration in the area. The construction of a permanent processing facility, Ekati™ Diamond Mine, began only 4 years later in 1995. In 1996 BHP Billiton received clearance from the NWT government to begin production and by 1998 diamonds were being extracted at a rate of 1 million dollars gross daily (BHP Diamonds Inc. 1999). Five other mines are close behind Ekati in various phases of construction with Diavik DeBeers only months away from production. Lupin, Colomac and Snap Lake mines are three smaller mines within 400 km of Yellowknife and with exploration expanding there will surely be more to follow (Appendix A, Figure 1). This study will focus on the Ekati™ Diamond Mine.

The Ekati™ Diamond Mine is located approximately 300 km north of Yellowknife and 200 km south of the Arctic Circle on Lac de Gras in the Northwest Territories (Appendix A, Figure 1). The area is considered a polar desert receiving an average 160 mm of annual precipitation, which falls almost exclusively between the months of May and October (BHP Diamonds Inc. 1994) (Appendix B, Table 1). Vegetation in the area consists of low growing mosses and lichens, sedges (*Carex* spp.) and numerous grass species. Dwarf birch and willow are also common in this Heath Tundra ecosystem (Kershaw 1987). Temperatures range between -40 °C in the winter and 25 °C in the summer (BHP Diamonds Inc. 1997). The summer growing season at the Ekati mine site is cool but luminous with the warmest months, August and September, having mean monthly temperatures of 10 and 12 °C, respectively, and an average of 18 hours of light daily (Appendix B, Table 1).

1.2 Disturbance of the Tundra Ecosystem

Human activities in the Arctic often cause long-lasting changes in tundra landscapes (Truett and Kertell 1992). Some of the most widespread changes result from disturbing the vegetation and surface soil through activities such as building roads, moving heavy equipment, driving heavy vehicles, impounding surface water and spilling oil or other contaminants (Truett and Kertell 1992). Visual signatures of such activities persist for many years, often expanding with time. The major reason for the continuing high visibility of surface disturbance in the Arctic is the process of thermokarst, by which the thawing of ice-rich soils beneath disturbed surfaces accelerates, causing the landform surface to subside (Truett and Kertell 1992). Surface disturbance often leads to thermokarst because it reduces the insulative value of the vegetation and surface soil, the landscape surface albedo, or both, enabling the summer sun to thaw the soil to greater depths then usual. Current territorial and federal environmental guidelines do not take these specific northern concerns into account and are based strongly on plans developed for more southern latitudes.

1.3 Legislation

In the Northwest Territories the federal government, through the Department of Indian Affairs and Northern Development (DIAND), is responsible for the management of water, hydrocarbons and mineral resources as well as the administration of most Crown land. The Canada Mining Regulations, made under the Territorial Lands Act, provide control over mineral rights on Crown land and payment of royalties to the Crown (Government of Canada 2002). These royalty regulations were amended in 1995 with the most notable change being the maximum royalty rate, which increased from 1% for each 5 million dollars profit to 14% (Government of Canada 2002). The main environmental regulations are, however, controlled provincially.

The NWT Water Resource Agreements Act and Department of Indian Affairs provide the main environmental protection for areas under mining development. The Water Resource Agreement Act is concerned with the disturbance of natural watersheds and is meant to protect natural drainage patterns and water quality (Government of the Northwest Territories 2000). The second measure of protection is based on the Environment Agreement between BHP Billiton, the NWT Government and the Department of Indian Affairs. This agreement is specific to the Ekati mine site and is based on a full environmental assessment of the area being disturbed and the development of a reclamation plan prior to disturbance (BHP Diamonds Inc. 1994). Through this process Ekati has agreed to stabilize all landforms affected by mining operations, including their dry tailings waste. The NWT government also has regulations in place for the use of explosives, storage and transport of chemicals, mineral exploration, fencing establishment, mining safety, motor vehicle use and waste disposal.

1.4 Kimberlite Mine Tailings

Kimberlite is defined as a very rare ultrabasic rock of coarse texture, which usually occurs in small diatremes and dykes in the earth's crust (Wyllie 1967). This study is specifically concerned with kimberlite tailings, which are the crushed kimberlitic ore materials left after diamond extraction. At Ekati™ Diamond Mine these waste materials are transported from the processing facility and dumped as a slurry into the natural basin of Long Lake Containment Facility (LLCF) (Appendix A, Figure 2). Tailings deposit began at the north end of LLCF and has progressively moved south creating a drainage slope from north to south (Appendix A, Figure 3). In spring 2000 tailings at the most northerly end of LLCF had significantly dewatered causing the tailings to become unstable.

The Ekati processed kimberlite tailings have several limitations in relation to plant growth including coarse texture, no organic component (poor water and nutrient holding capacities), low macronutrients, dark colour and an unbalanced calcium magnesium

fraction (Table 2.1). The amendment of these structural and nutrient limitations through testing of several different amendments will be the main focus of reclamation efforts. Peat moss, lake sediment, sewage sludge, paper mill waste, Agri-boost, fertilizer and three calcium sources (gypsum, rock phosphate and calcium carbonate) will be evaluated alone and in combination in relation to improving these kimberlite tailings as a plant growth medium.

1.5 AMENDMENTS

Peat moss is a common soil amendment used when nutrient deficiencies and water stress are present. Neilson et al. (1997) studied crop yield in a sandy soil with low available nutrients and water stress. They showed that peat moss application at a rate of 45 t ha^{-1} significantly increased water and nutrient holding capacities of this agricultural soil and resulted in increased crop yields. Moskal et al. (2001) using peat moss in oil sand tailings reclamation, found that it significantly improved water holding capacity, bulk density, field capacity and permanent wilting point. The texture of these oil sand tailings was altered from a sandy texture to a loamy sand texture by the addition of peat moss. In a third study (Al-Kanani et al. 1992) using peat moss amendment on coarse textured materials nitrogen losses were considered after hog manure application. The results of this study show a significant decrease in the volatilization of ammonia (NH_3) and loss of nitrogen (N) after peat moss application without a significant reduction in the effectiveness of residual nitrogen. This study proposes that peat moss retains NH_3-producing compounds in its structure and the acid pH of the peat moss reduced NH_3 volatilization when the peat moss is mixed with manure.

The sewage sludge tested in this study was produced at the Ekati mine and is being considered as both a nutrient source and a structure improving amendment. Sewage sludge has been used successfully as a nutrient source in agricultural studies improving macronutrient availability in the rooting zone (Neilsen et al. 1997). Sewage sludge application has also improved soil surface structure and significantly reduced erosion by

wind and runoff waters (Bresson et al. 2001). There are however, human health issues associated with fecal coliform and streptococci bacterial populations in biosolid materials. Edmonds (1976) showed that 64 days after sewage sludge application, in the summer season, coliform levels were reduced by almost 80% of original levels and after 200 days were less then 1% of the application levels. With winter application the rate of survival is even more reduced and after 162 days 0.02% of the original coliform levels were present and after 343 days 0% remain (Edmonds 1976). For Ekati this translates to 136 colony forming units (CFU) L^{-1} after 162 days, which is well below the United States Code of Federal Regulations for waste discharge, which recommends 2000 CFU L^{-1} (Dunigan and Dick 1980).

Lake sediment from Koala Lake is also being considered in this study as a structure improving amendment. Kidd (1999) conducted a greenhouse study evaluating plant growth of several native transplants and sown natives including *Poa alpina*, *Deschampsia caespitosa* and *Festuca rubra* on Koala Lake sediment materials. Kidd concluded that Koala Lake sediment could sustain plant growth. However, the fine particle size was better suited for wetland vegetation and the lack of organic material could inhibit long-term plant survival. Kidd recommended that lake sediment be applied in combination with an organic carbon source and a nutrient source for early plant establishment and survival.

Papermill sludges are a result of sedimentation from the wastewaters produced in a typical pulping process. About 50 kg dry paper mill sludge is produced for every tonne of pulp produced (Belsito and Winterhalder 1999). This waste material consists mainly of cellulose fibres (typically 50 to 60%), fine fillers such as clay (10 to 25%) and calcium carbonate (10 to 25%) with smaller amounts of coating materials and processing chemicals (Belsito and Winterhalder 1999). The current disposal options for this pulp waste material include land filling, incineration, reuse as a fibre source or land application. The use of this sludge to amend the Ekati processed kimberlite tailings will increase organic matter, improve the coarse texture of the tailings and act as a source of

calcium. Paper mill sludge has increased water and nutrient holding capacities of soil and acts to stabilize highly erodable substrate (Belsito and Winterhalder 1999).

Argi-Boost, a commercially available soil conditioner, was also considered as a structural amendment. Agri-Boost is made of ground, all-natural minerals and materials, including zeolites, palagonite, olivine and calcite, all of which are derived from balsatic ash (Table 2.2). Agri-Boost has a high water holding capacity, and most of this held water is plant-available. In a study of soil amendments for golf putting greens only peat moss held more plant-available water in the root zone mix than Agri-Boost (Stoklas 1999). Agri-Boost has a very high cation exchange capacity (CEC): 56 meq 100 g^{-1} for divalent cations like calcium (Ca), magnesium (Mg), potassium (K) and ammonium (NH4+) (Stoklas 1999). Agri-Boost is expected to improve the structure of the Ekati kimberlite tailings and aid in retaining macronutrients added in combination with this structure enhancing amendment.

The four mineral-nutrient amendments, being tested in this study, were fertilizer, calcium carbonate, gypsum and rock phosphate. The fertilizer was a standard commercially available fertilizer (10-34-10-5) boosted with ammonium nitrate (33-0-0). The availability of N is critical to establishment of vegetation on disturbed lands (Palmer 1987). Palmer (1987) suggests that there are two common points of interruption in the N cycle on disturbed lands, mineralization and nitrification. If the carbon (C) to N ratio is not properly balanced, microorganisms cannot effectively decompose organic matter and N availability is reduced. Other factors such as pH can affect microbial activity and are common on disturbed lands such as mine waste materials (Palmer 1987). Palmer (1987) concludes that to establish a self-sustaining vegetation on disturbed lands, N inputs are essential in developing a capital of nutrients and restoring the N cycle. However, he also concludes that high levels of fertilization can lead to the promotion of high biomass production and an imbalance in the C:N ratio subsequently reducing N available to plants and prompting further fertilizer inputs. Palmer (1987) suggested that legumes providing steady but low levels of N can be more effective in sustaining a plant community, resulting in balanced C:N levels and more diverse plant communities.

The serpentine condition of the Ekati kimberlite tailings is based on its Ca:Mg ratio. Serpentine soils are characterized by Ca/Mg fractions below 0.8 (Smith and Burgess 1986). The Ekati kimberlite tailings have a Ca/Mg fraction of 0.58, which is inhibiting to plant establishment and growth (Smith and Burgess 1986). The addition of Ca to serpentine soils has shown improved substrate water storage capacity, reducing soil sodicity and balancing Mg levels, overall improving substrate conditions in relation to plant growth (Schuman and Meining 1993). The effects of surface applied Ca sources are often not observed until the third growing season illustrating the time required for these amendments to dissolve and become an effective soil nutrient (Schuman et al. 1994).

1.6 Waste Materials in Reclamation

The remote location of the Ekati™ Diamond Mine increases the challenge of large-scale mine reclamation and raises the question of resource utilization efficiency (Section 2.3.1). With a winter road open only 3 months of the year the cost of shipping materials to the mine site is high, as most supplies must come by air (BHP Diamonds Inc. 1997). This high cost of transporting material has prompted the consideration of using alternative or waste materials in mine reclamation. In this study three waste materials, sewage sludge, paper mill waste and lake sediment were tested as alternatives to more traditional soil conditioners like peat moss and fertilizer (section 2.3.3).

Peat moss harvest for commercial resale begins with drainage of a peat moss bog. Plant material, stumps, roots and debris are removed from the area. Harrows loosen the top peat moss, which then dries in the sun for two to three hours before being vacuumed into large harvesters. It is transported from the field to the plant where it is screened, graded and baled for storage or shipment (Industrial Minerals: Sphagnum Peat Moss 2002). The drainage and excavation of peat lands contributes to the total area of land disturbed and to the loss of habitat, which is today considered the number one contributing factor to species extinction (Smith 1992). The degradation of peat lands to amend soil conditions

on other disturbed lands is counter productive to the overall goal of reclamation, which aims to amend disturbed lands reducing impact to the natural environment (BHP Diamonds Inc. 1994).

Mineral fertilizer production comes at a cost to the environment (Mayer 1996). The production of fertilizer involves raw mineral extraction as well as chemical reactions at high temperatures and pressures. The transformation of these raw materials inherently leads to by-products, emissions and wastes such as ammonia, nitric acid, urea, sulphuric acid, phosphoric acids and carbon dioxide (Mayer 1996). The support of fertilizer production again seems in contrast with the overall efforts of reclamation.

The use of waste material is more suitable for reclamation efforts as these materials are often inevitable by-products of resource utilization and must be dealt with anyway. Papermill sludge, a by-product of the pulp industry has shown excellent performance as an organic source, improving water and nutrient holding capacities (Section 2.4) (Belsito and Winterhalder 1999). Sewage sludge has shown promise as a nutrient source in both field and greenhouse experiments (Sections 2.4 and 3.4) (Miles and Tainton 1979, Dunigan and Dick 1980). This waste material is produced at the mine and has no purchase cost. By using it in reclamation, treatment and disposal costs are reduced.

The costs associated with specific amendments in reclamation must not only be measured in dollars but also in the environmental cost associated with use. If true reclamation is to occur, overall environmental impact must be reduced, not transferred from one industry to another. The use of waste materials can be beneficial to both aspects of cost. In this study the waste materials papermill sludge, sewage sludge and lake sediment had no purchase cost and actually reduced environmental cost by productively disposing of another's by-products. Compared to peat moss and mineral fertilizer the use of waste materials seems more responsible to the objectives of reclamation.

The harvest of our natural resources, by its nature, results in disturbance to the environment (Sopher and Baird 1982). It is important to reduce and repair these

disturbances minimizing the footprint left by industry. The discovery of diamonds in the Canadian Arctic is economically important, however, the extraction of this resource should not come at the expense of this vital ecosystem (BHP Diamonds Inc. 1998). As this new industry develops it will be important to set high standards demanding a reasonable balance between profit and impact.

1.7 Research Outline

This research focused on stabilizing Ekati's processed kimberlite tailings with a self-sustaining vegetation cover and thereby reducing the environmental impact of mining practices on the area. The tailings wastes produced at Ekati mine have a number of physical and chemical limitations inhibiting plant growth. Examining physical and chemical amendments to improve the ability of these tailings to sustain plant growth is essential if a permanent, self-sustaining vegetation cover is to be established.

This research was carried out in two phases, a laboratory/greenhouse study and a field study. The laboratory study evaluated the chemical and physical properties of potential amendments followed by a greenhouse study testing these amendment combinations in relation to plant growth and tailings properties (Chapter 2). The more promising amendment combinations were tested in the field on the Ekati kimberlite tailings containment area (LLCF), where plant growth and substrate improvement were monitored over two growing seasons (Chapter 3) (Appendix A).

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CHAPTER II. ESTABLISHEMENT OF A VEGETATION COVER ON KIMBERLITE MINE TAILINGS: GREENHOUSE STUDY

2.1 INTRODUCTION

The discovery of kimberlite diamonds in the Northwest Territories (NWT) in 1991 by Charles Fipke and Stewart Blusson has resulted in the largest staking rush in Canadian history and the establishment of several mining operations including Diavik, Colomac, Snap Lake, Lupin and Ekati Diamond Mines (Appendix A, Figure 1) (BHP Diamonds Inc. 1994). Prior to this discovery, diamond rich kimberlite deposits were mainly mined in South and Western Africa at several mine sites including Palmietgat, Venetia, Aredor and Camafuca Diamond Mines.

Kimberlite is defined as a very rare ultrabasic rock of coarse texture, which usually occurs in small diatremes (pipes) and dykes in the earth's crust (Wyllie 1967). Kimberlitic materials are characterized as having low nutrient availability, poor water and nutrient holding capacities and poor overall structure (Miles and Tainton 1979a, Grigor and Williams 1999, Wienhold and Tanaka 2001). Soils parented by kimberlitic material are consequently underdeveloped and often sparsely vegetated. Despite poor vegetation cover, naturally occurring kimberlite pipes pose minor erosive potential as they are usually smaller then a hundred meters in diameter and often found in protected depressions or under lakes.

The extraction of diamonds from kimberlite is accompanied by the production of large quantities of waste rock or tailings (Miles and Tainton 1979a). High volumes of kimberlite tailings are usually deposited in surface containment facilities, resulting in significant areas of land being covered by exposed kimberlite materials. With no protective surface cover and a large exposed surface area, dewatered kimberlite tailings have a high erosive potential, which can result in redeposition of tailings materials on the surrounding undisturbed lands. Stabilization of these waste materials is therefore a critical component of impact reduction and an important aspect of mine operations in an

increasingly environmentally conscious world. Several methods for stabilizing kimberlite mine tailings may be implemented including capping with other waste rock materials, flooding or vegetating. Numerous site-specific factors may dictate the appropriate action (Kershaw 1987). The most popular method of stabilizing tailings waste is with a vegetation cover. However, it can be difficult on kimberlite tailings as they often exhibit unsuitable substrate properties for plant colonization (Cox and Hutchinson 1980).

Past consideration in using a vegetation cover to stabilize processed kimberlite tailings focused on plant species selection (Miles and Tainton 1979a). In most tailings revegetation research, plant species tolerance to specific substrate conditions are evaluated and reclamation recommendations are based on these tolerances (Cox and Hutchinson 1980, Grigor and Williams 1999, Winterhalder 1992).

This study investigated the stabilization of the Ekati^{TM} Diamond Mine kimberlite tailings with a vegetation cover, focusing on tailings amendment in relation to plant growth rather then species tolerance to poor conditions. Structural improving and nutrient providing amendments were tested in various combinations and application rates. This research consists of two components: (i) a series of greenhouse studies identifying the Ekati kimberlite tailings limitations to plant growth and testing amendments to address these limitations, and (ii) a field study assessing amendment effect on kimberlite tailings properties and plant growth at the Ekati mine. The greenhouse component will be addressed in this chapter.

2.2 Objectives and Hypotheses

2.2.1 Objectives

The overall objective of this greenhouse study was to assess structural enhancing and nutrient providing amendments to improve the Ekati kimberlite tailings as a plant growth medium facilitating the establishment of a permanent vegetation cover.

The specific objectives were:

1. To assess the effect of amendments on the Ekati kimberlite tailings properties (available nitrogen, phosphorus, potassium and sulphur, cation exchange capacity, total organic carbon, total calcium and total magnesium).
2. To assess the effect of amendments on the Ekati kimberlite tailings in relation to plant response (height, health, ground cover, root/shoot biomass).
3. To assess the effect of rate of application of amendments on the kimberlite tailings properties and plant response.

2.2.2 Hypotheses

1. The addition of nutrient providing amendments will significantly increase the available macronutrients in the Ekati kimberlite tailings.
2. The addition of structure improving amendments will significantly increase the cation exchange capacity and percent organic carbon of the Ekati kimberlite tailings.
3. The most effective amendment combinations in relation to plant response will include both a structure improving amendment and a nutrient source.
4. The addition of calcium carbonate, gypsum or rock phosphate to the Ekati kimberlite tailings will increase the total calcium, ameliorating the tailings serpentine state and establishing a more natural calcium, magnesium fraction of 2.

2.3 Materials and Methods

2.3.1 Site Description

The Ekati™ Diamond Mine is located approximately 300 km north of Yellowknife and 200 km south of the Arctic Circle in the Canadian Northwest Territories (Appendix A, Figure 1). The mine is located in a heath tundra ecosystem, parented by Precambrian granite swept clean by glaciations of the last ice age. Boulder fields, sand eskers and countless lakes cover the landscape. The area receives approximately 160 mm of precipitation annually which almost exclusively falls between July and October. Temperatures range between -40 and 25 °C with only four months of the year having mean temperatures over 0 °C (Appendix B Table 1) (BHP Diamonds Inc. 1997).

The kimberlite tailings at Ekati™ Diamond Mine are pumped from the processing facility and deposited into the natural basin of Long Lake Containment Facility (LLCF), approximately 15 km away (Appendix A, Figure 2). LLCF was a sequence of headwater lakes that have been excluded from the water shed by a series of frozen dams and divided into five containment cells (A through E) (Appendix A, Figure 3). In spring 2000 tailings at the most northerly end of LLCF had significantly consolidated causing them to become unstable and highly susceptible to wind and water erosion.

2.3.2 Ekati Kimberlite Tailings

The Ekati Diamond Mine kimberlite tailings have a number of physical and chemical limitations (Table 2.1). The tailings are low in macronutrients and have low cation exchange capacity (CEC) (1.95 meq 100 g^{-1}), which can be attributed both to the lack of organic carbon and the coarse texture of this substrate (Smith 1992). The dark grey colour of the substrate promotes high summer surface temperatures and thus a rapid evaporative loss of moisture from the upper surface layers (Miles and Tainton 1979b). The kimberlite tailings used in this greenhouse study were collected from the north end of LLCF in August 2000.

2.3.3 Amendments

Amendments were selected to ameliorate tailings limitations. These amendments can be divided into two main groups, structure improving (peat moss, lake sediment, sewage sludge, Agri-Boost and composted papermill sludge) and nutrient providing (fertilizer, calcium carbonate, gypsum and rock phosphate). Sewage sludge worked to improve substrate structure and nutrient availability and was considered in both categories. Amendments high in organic matter such as peat moss, Agri-Boost and papermill sludge will decompose with time, providing mineral nutrients to the tailings (Smith 1992). However, these amendments were primarily considered for their structural improvement not nutrient provision.

Good structure is an essential part of a productive terrestrial soil (Brady and Weil 1996). Organic material in a soil increases water and nutrient holding capacities, reduces soil compaction, increases aeration of the rooting zone and promotes microbial activity, all which contribute to a more favourable plant growth environment (Campbell 1996, Cheng et al. 1998). Peat moss, sewage sludge, Agri-Boost and papermill sludge were all selected to increase organic matter in these tailings, improving overall structural (Appendix B).

Studies using peat moss and papermill waste as organic sources to improve substrate structure have shown that both amendments increase water and nutrient holding capacities, reducing erosion potential, and facilitating favourable plant response (Belsito and Winterhalder 1999, Winterhalder 1992). Agri-Boost exhibited similar beneficial properties in a greenhouse study considering plant germination and survival on sandy soils (Stoklas 1999). Agri-Boost improved water and nutrient holding capacities and nutrient availability resulting in higher canola (*Brassica napus*), barley (*Hordeum vulgare*) and clover (*Trifolium repens*) establishment, survival and shoot biomass (Stoklas 1999).

Lake sediment was selected for testing as a structure improving amendment. Lake sediment is readily available at the mine site and represents the overburden removed from Koala Pit after lake drainage and before kimberlite extraction. Lake sediment is more

diverse in texture than the processed kimberlite tailings with a silt content of 54.3% and a clay content of 15.3% (Table 2.2). The addition of these finer particles to the coarse textured tailings was expected to improve overall structure creating a more loam textured substrate. Loamy soils are often the most fertile having enough fine particles to provide a large surface area for retaining minerals and water, which adhere to the finer particles (Campbell 1996). However, larger particles are needed to provide adequate air spaces in the soil essential for root cellular respiration (Campbell 1996).

This Koala Lake sediment was evaluated as a growth medium in a greenhouse study by Kidd (1999) (Table 2.2). Kidd found the lake sediment was suitable for plant growth but lack of organic matter contributing to water stress and low available nutrients could inhibit long-term vegetation success. Kidd suggested that if lake sediment was to be a successful plant growth medium it would need to be combined with a nutrient source and an organic source.

The sewage sludge tested was produced at the mine site and was mainly untreated. It contained quantities of organic material and high fecal coliform and streptococcus levels (Table 2.2). In addition to organic matter benefits the sewage sludge provided essential plant macronutrients, nitrogen (N), phosphorus (P), potassium (K) and sulphur (S). These four macronutrients must be present in appropriate quantities if sustainable plant growth is to occur (Campbell 1996).

The use of sewage sludge as a soil amendment is becoming increasingly attractive as research supports the benefits of its use and combats the risks associated with application. Research on nutrient runoff loss comparing sewage sludge to commercial fertilizer suggests that when incorporated into the soil surface, sewage sludge exhibited macronutrient leaching rates equal to, or lower than, those of fertilizer amended soils (Dunigan and Dick 1980). The sewage sludge amended soil can produce a better long-term source of plant nutrients, as decomposition of organic material in sludge will continue to make nutrients available over time (Dunigan and Dick 1980). Application risks associated with sewage sludge were considered in this study. Fecal coliform counts

dropped from 13,000 FC ml^{-1} at time of application to 86 FC ml^{-1} in 53 days (Dunigan and Dick 1980). It was suggested that dry conditions and or cool temperatures would accelerate this bacterial loss (Meeting 1992).

Fecal coliform and streptococcus levels in the Ekati sewage sludge were high at 6.8×10^6 colony-forming units 100 ml^{-1} (CFU) and 3.4×10^6 CFU 100 ml^{-1}, respectively. These levels can be dangerous to unprotected humans in direct contact with the sewage sludge. Basic protective coverings when applying the sewage sludge were sufficient for protection. With a late fall or early spring application of sewage sludge these high bacterial counts will not be a health factor for long (Dunigan and Dick 1980).

Commercial fertilizer was also tested as a nutrient improving amendment. The Westco brand (10-34-10-4) fertilizer consisted of 10% water-soluble nitrogen, 34% available phosphoric acid (H_3P0_4), 10% soluble potassium and 4% sulphur. Ammonium nitrate was added at a rate of 10 grams for every 36 g of fertilizer (ammonium nitrate 34-0-0) containing 34% soluble nitrogen.

Three calcium sources were also tested as nutrient improving amendments. Calcium carbonate, gypsum and rock phosphate were selected to raise the level of calcium restoring a more natural calcium magnesium ratio of 2:1 (Whittaker 1954, Koide and Mooney 1987). The powdered gypsum ($CaSO_4$) contained 20.1% calcium and was applied at a rate of 2173 kg ha^{-1}, which was calculated based on the magnesium levels (17.7 meq 100 g^{-1}). Rock phosphate had a calcium content of 24% and was applied at a rate of 2080 kg ha^{-1}. Calcium carbonate had a calcium content of 39% and was applied at a rate of 1667 kg ha^{-1}. The calcium carbonate was used in a granular form, not to further raise the tailings pH.

2.3.4 Reclamation Species

Seven perennial grass species [*Arctagrostis latifolia* (polar grass), *Calamagrostis canadensis* (bluejoint), *Poa glauca* (tundra bluegrass), *Poa alpina* (alpine bluegrass),

Deschampsia beringensis (bering hairgrass), *Festuca rubra* (creeping red fescue) and *Deschampsia caespitosa* (tufted hairgrass)] were selected as indicators of amendment success (Appendix C). Selection was based on suitability to the heath tundra ecosystem at Ekati™ Diamond Mine and potential contribution to the sustainable stabilization of these tailings. All of these species are native cultivars developed for reclamation in alpine and northern latitudes and have good erosion control growth forms and high potential to facilitate native invasion on disturbed sites (Mitchell 1980). The species were mixed in a 1:1 ratio by seed weight to ensure that each was equally represented in the seed mix (Appendix C, Table 1).

2.3.5 Greenhouse Procedures

The greenhouse study ran from October 2000 to October 2001. Due to space constraints and the large number of variables to be tested, the study was divided into three, four-month sessions. The first week of each 16-week session was used for preparing amendment combinations. Pots were filled with the appropriate mixtures, seeded and given 14 weeks to germinate and grow. Harvest and final quantification of results occurred in the final week of each session.

Combinations tested in the greenhouse were based on amendment feasibility and availability for field application. The first greenhouse session was designed to establish a comparison criteria between the field and greenhouse components of this study. The second and third greenhouse sessions aimed to broaden the scope of the project by addressing amendment application rates and additional combinations not field tested (Appendix D, Tables 1).

Standard greenhouse pots (12.5 cm in diameter and 15 cm deep), with four drainage holes, were used. Each pot was lined with black polyfill bedding cloth (Easy Gardener landscape fabric) to prevent the coarse textured tailings from falling out of drainage holes and to speed root harvest as most of the root material adhered to the cloth.

Peat moss, lake sediment and sewage sludge were applied by volume (Appendix D). This ensured that each pot would receive the appropriate proportion of amendment in relation to the field plots. This is important in calibrating the greenhouse with the field as dilution of the processed kimberlite tailings by an amendment is expected to have an effect on plant response. Chemical amendments (gypsum, rock phosphate, calcium carbonate, fertilizer and ammonium nitrate) were applied by weight per unit area (Appendix D).

Amendment distribution in the tailings profile was an important factor. Amendments were measured, placed in a five-gallon pail in the appropriate combinations and mixed before each pot was filled, simulating the field rotovation. Sewage sludge was applied by volume to the surface of each pot and allowed to soak in overnight. The contents of each pot were then emptied into a five gallon pail and mixed to simulate field rotovation. The papermill sludge and Agri-Boost were applied by volume to simulate field application rates of 2 and 4 cm rotovated to a depth of 25 cm.

Once the pots were filled they were moved from the lab to the greenhouse and saturated with 400 ml of deionised water. The pots were allowed to sit overnight under greenhouse conditions and were again saturated (400 ml pot^{-1}) prior to seeding. The seed and fertilizer were weighed out individually for each pot and hand broadcast over its surface. Species proportion was calculated based on seed weight to create a mix where all seven species were equally represented (Appendix C, Table 1).

Once seeding was complete, pots were kept at field capacity as determined by the filter paper method (Alef and Nannipieri 1995). To maintain each pot at field capacity 250 ml of deionised water was added every 24-hour period (Appendix B, Table 2). The greenhouse temperature and hours of light were regulated to simulate natural conditions at the mine's latitude. Light was kept constant at 18 hours per day, simulating the long hours of daylight during Ekati's summer months. The temperature was kept fairly cool between 15 and 21 °C, simulating the cool mean monthly conditions for the growing season (July, August, September) (Appendix B, Table 1).

2.3.6 Quantification of Plant Response

Amendment success in the three greenhouse sessions was based on several aspects of plant growth. Ground cover, root and shoot biomass, plant height, plant development and plant health were measured at the end of each 14-week greenhouse session. All assessments were conducted by the same person to reduce errors.

Ground cover was estimated as a percent of the total surface area of each pot covered by shoot vegetation. The tallest individual plant in each pot was measured (maximum height) and the mean height of all plants in each pot (mean height) was estimated. Plant development was visually assessed by noting the presence or absence of flowering and/or tillering in each pot. Each pot was given a value between 1 and 4 based on the overall visual health of all plants. Colour, number of dead individuals and general robust appearance were all taken into account in this assessment. Pots containing >50% dead individuals were assessed a health value of 1; pots with 25 to 50% dead individuals were given a 2; pots with 5 to 25% dead individuals were given a 3; and pots with green robust cover and less then 5% dead individuals were assessed a 4. Finally all plant material was removed, washed, divided into roots and shoots, oven dried at 90 °C for 48 hours and weighed to determine biomass for each pot.

2.3.7 Soil Analyses

Approximately 500 g of substrate was collected from each pot during harvest. The sample was shaken out of the plant roots and supplemented with residual material left in each pot. All samples were sent to EnviroTest Laboratories in Edmonton, Alberta for analysis. Each sample was analysed for the following: available nutrients (N, P, K, S), pH, total cations (Ca, Mg, Na, K), CEC, extractable cations (Ca, Mg, Na, K), total carbon and total inorganic carbon. Available P and K were determined using a modification of the Kelowna Extraction method (Qian et al. 1994). Available N and S were determined as NH_4^+, NO_3^- and SO_4^{-2} by a calcium chloride extraction method (Carter 1993). Substrate pH was measured using a saturated soil paste method (McKeague 1978). Total

cations was determined by a saturated paste method (Carter 1993). CEC and extractable cations were determined by the NH_4O ammonium acetate extraction method (McKeague 1978). Total carbon was determined using a Leco Furnace combustion method (Carter 1993). Total inorganic carbon was determined by dissolution with hydrochloric acid (Carter 1993). Total organic carbon was calculated as the difference between total carbon and total inorganic carbon.

2.3.8 Experimental Design

Each of the three greenhouse sessions consisted of a randomized complete block design. Thirty-four amendment combinations were tested in the first session, which focused on a field vs. greenhouse comparison (Appendix D) and ran from October 2000 to January 2001.

The second session, running from January to April 2001, focused on application rates of peat moss, lake sediment and sewage sludge. The experimental design consisted of 5 peat moss rates (0, 2, 4, 6 and 8 cm) x 4 lake sediment rates (0, 5, 10 and 15 cm) x 4 sewage sludge rates (0, 5, 10 and 15 cm) x 1 calcium treatment (2173 kg ha^{-1} gypsum + 2080 kg ha^{-1} rock phosphate) x 1 fertilizer treatment (280 kg ha^{-1}) x 1 perennial species x 3 replicates = 240 pots.

The third greenhouse session running from May to August 2001, assessed chemical amendment rates and tested additional amendments (papermill sludge and Agri-Boost). The design consisted of 3 gypsum rates (1087, 2173 and 3259 kg ha^{-1}) x 3 rock phosphate rates (1040, 2080 and 3120 kg ha^{-1}) x 3 calcium carbonate rates (833, 1667 and 2500 kg ha^{-1}) x 3 fertilizer rates (140, 280 and 420 kg ha^{-1}) x 4 physical amendments (peat moss 2 cm, lake sediment 5 cm, sewage sludge 5 cm and no physical amendment). To reduce combination repetition all combinations previously tested in greenhouse sessions 1 and/or 2 were eliminated. Treatments of Agri-Boost and papermill sludge were tested at two application rates (2 and 4 cm) in combinations with and without calcium amendment

(gypsum 2173 kg ha^{-1} and rock phosphate 2080 kg ha^{-1}). These additional combinations brought the total number of pots to 200.

2.3.9 Statistical Analyses

Data were first organized and ranked for each parameter measured. An overall ranking was determined by summing the individual ranking scores for each plant growth parameter (Table 2.3). Amendment performance within each greenhouse session was compared using orthogonal contrasts (Petersen 1994) allowing the effect of individual amendments to be considered for each plant parameter measured. Using orthogonal contrasts all amendment combinations containing a given amendment (e.g. sewage sludge) could be grouped and compared to all other amendment combinations (e.g. not containing sewage sludge). The means of these two groups were compared in a linear function testing the hypothesis that the contrast is zero against the contrast statement not equalling zero. If the contrast statement does not equal zero it indicates the amendment groupings are significantly different. This statistical method allowed grouped comparisons and can be used to isolate amendment effects within a combination series (Petersen 1994). Duncan's Multiple Range test was used to make overall amendment comparisons. T-tests were used to make more specific comparisons between individual amendment combinations.

2.4 Results

2.4.1 Amendment Effect on Plant Growth

The top ten amendment combinations in relation to plant response included both a structure improving and a macronutrient providing amendment (Table 2.3). Of the ten lowest ranked amendment combinations only one contained both a structure improving and nutrient providing amendment and that was sewage sludge alone. Four of the 13 middle combinations contained both a structure improving and nutrient providing

amendment (Table 2.3). The most common amendment (8 out of 10) in the top 10 combinations was sewage sludge. Peat moss was second (6 out of 10) and fertilizer followed (4 out of 10). Sewage sludge was only present in 1 of the middle 13 combinations and 1 of the bottom 10 combinations (Table 2.3). Peat moss was present in 4 of the middle 13 combinations and 1 of the bottom ten combinations with fertilizer present throughout the top 10 and middle 13 but showing no presence in the bottom 10 combinations.

Preliminary testing showed papermill sludge had a promising effect on plant growth. Papermill sludge significantly increased ground cover with 3 out of 4 papermill sludge combinations resulting in ground covers between 76 and 85%. Agri-Boost did not show as much promise with the four amendment combinations ranging from 30 to 48% ground cover. These preliminary trial amendments showed similar trends for shoot and root biomass and plant height.

2.4.1.1 Ground Cover

The addition of peat moss, sewage sludge or fertilizer to the kimberlite tailings resulted in a significant increase in ground cover. Peat moss, gypsum, rock phosphate and fertilizer, produced the highest ground cover at 62% compared to the unamended control at 17% (Table 2.4). All of the top 10 amendment combinations included either peat moss or sewage sludge or both in combination (Table 2.3). Fertilizer was present in only 4 of the top 10 amendment combinations. Ground cover was not significantly affected by the lake sediment or any of the three calcium sources (gypsum, rock phosphate, calcium carbonate). Nine of the ten best ground cover producing amendment combinations contained both a structure improving and a nutrient providing amendment (Appendix E).

2.4.1.2 Shoot Biomass

The addition of peat moss, sewage sludge or fertilizer to the kimberlite tailings resulted in a significant increase in shoot biomass. Peat moss, gypsum, calcium carbonate and fertilizer produced the highest shoot biomass with a mean of 1.72 g pot^{-1} compared to the unamended control at 0.26 g pot^{-1} (Table 2.4). Eight of the 10 best shoot biomass

producing amendment combinations included sewage sludge (Table 2.3). Fertilizer was present in 5 of the top 10 as was peat moss. Shoot biomass was not significantly affected by lake sediment or any of the three calcium sources (Appendix E). All top 10 shoot biomass producing amendment combinations contained both a structure improving and a nutrient providing amendment.

2.4.1.3 Root Biomass

The addition of peat moss, sewage sludge or lake sediment resulted in a significant increase in root biomass. The combination of lake sediment and sewage sludge resulted in the highest root biomass with 2.20 g pot^{-1} compared to the unamended control at 0.28 g pot^{-1} (Table 2.4). Seven of the top 10 root biomass producing amendment combinations included peat moss (Table 2.3). Sewage sludge was present in 5 of the top 10 combinations and lake sediment or fertilizer was present in 3 of the top 10 combinations. Root biomass was not significantly affected by fertilizer or any of the three calcium sources (Appendix E). Seven of the top 10 root biomass producing combinations contained both a structure improving and a nutrient providing amendment (Table 2.3).

2.4.1.4 Plant Height

Sewage sludge, lake sediment, calcium (gypsum, rock phosphate, calcium carbonate) or fertiliser significantly increased plant height. Lake sediment, sewage sludge, gypsum and rock phosphate produced the tallest plants with a mean height of 28 cm compared to the unamended control at 12 cm (Table 2.4). Nine of the top 10 plant height producing amendment combinations included one of the three calcium sources (Table 2.3). Sewage sludge was present in 7 of the top 10 combinations, 5 included fertilizer and 3 included lake sediment. Plant height was not significantly affected by peat moss. Eight of the top 10 amendment combinations in relation to plant height contained both a structure improving and a nutrient providing amendment (Table 2.3).

2.4.2 Amendment Effect on Kimberlite Tailings Properties

2.4.2.1 Available Macronutrients

Sewage sludge significantly increased available N, P, K and S. Peat moss and fertilizer significantly increased available N and P but did not significantly increase K or S (Table 2.5). Lake sediment significantly decreased available N, P, K and S. The combination of peat moss and sewage sludge resulted in the highest available N at 10.5 mg kg^{-1} compared to the control at 1.8 mg kg^{-1}. Sewage sludge was present in 4 of the top 10 amendment combinations in relation to available N and fertilizer was present in 5 of the top 10. The combination of peat moss, sewage sludge, gypsum, rock phosphate and fertilizer produced the highest levels of available P at 59.3 mg kg^{-1} compared to the control at 10.5 mg kg^{-1} (Table 2.5). This amendment combination was the second most successful in producing high available N. Sewage sludge was present in only 2 of the top 10 amendment combinations in relation to available phosphorus and fertilizer was present in all of the top 10. Available K was highest in amendment combinations that included peat moss, gypsum and rock phosphate, resulting in 237 mg kg^{-1} available K in comparison to the control at 192 mg kg^{-1} (Table 2.5). Sewage sludge was present in only 2 of the top 10 amendment combinations in relation to available K and fertilizer was present in 4 of the top 10. Available S was highest in amendment combinations that included gypsum and rock phosphate, resulting in 1021 mg kg^{-1} available S in comparison to the control at 285 mg kg^{-1} (Table 2.5). Five of the top 10 S producing amendment combinations included sewage sludge and only 3 of the top 10 included fertilizer.

2.4.2.2 Cation Exchange Capacity and Percent Organic Carbon

Sewage sludge and peat moss significantly increased CEC and organic carbon of the kimberlite tailings (Table 2.6). Peat moss and sewage sludge resulted in a CEC of 23.3 meq 100 g^{-1} (Table 2.5). Lake sediment significantly decreased CEC. Fertilizer and all three calcium sources had no significant effect on CEC or total organic carbon. Nine of the top 10 CEC enhancing amendment combinations included peat moss and 5 contained sewage sludge. Lake sediment was not present in any of these 10 best CEC amendment combinations (Table 2.6). The 10 best organic carbon enhancing amendment

combinations contained peat moss, 4 contained sewage sludge and 1 contained lake sediment.

2.4.2.3 Calcium, Magnesium Balance

The fraction of available calcium to available magnesium in the unamended kimberlite tailings was 0.97 (Ca = 17.125 meq 100 g^{-1}, Mg = 17.729 meq 100 g^{-1}) (Table 2.6). Peat moss, gypsum and calcium carbonate in combination raised the available calcium level to 21.13 meq 100 g^{-1}, the highest of any combination. This however, did not result in a significant improvement in the calcium magnesium fraction. The calcium magnesium fraction for this greenhouse study ranged from 0.86 to 1.47 with a mean of 1.12 and a standard deviation of 0.16.

2.4.3 Rate of Amendment Application Effect on Plant Growth

2.4.3.1 Ground Cover

Sewage sludge, peat moss and fertilizer application rates significantly affected ground cover. Sewage sludge at 10 cm did not significantly change ground cover from that of a 5 cm application. The 15 cm application showed significant increases over both the 5 cm and 10 cm application rates (F=0.0001) (Table 2.7). Peat moss application rates followed a similar trend with a 4 cm rate significantly increasing ground cover over a 2 cm rate (F= 0.0001). However, when the peat moss rate was further increased to 6 and 8 cm, no significant increase in ground cover was observed (Table 2.7). As the rate of fertilizer was increased from 140 to 420 kg ha^{-1} ground cover significantly increased (F=0.0063). However, no significant difference in ground cover was observed between 140 and 280 kg ha^{-1} of fertilizer. Rate of lake sediment, gypsum, calcium carbonate and rock phosphate had no significant effect on ground cover.

2.4.3.2 Shoot Biomass

Sewage sludge and fertilizer application rates resulted in a significant increase in shoot biomass. Sewage sludge at 10 cm did not significantly increase shoot biomass over that at 5 cm. However, sewage sludge at 15 cm showed a significant increase over both 5 and

10 cm application rates (F=0.0351) (F=0.001) (Table 2.7). As the rate of fertilizer was increased from 140 to 420 kg ha^{-1} shoot biomass significantly increased (F=0.0036). However, no significant difference in shoot biomass was observed between 140 and 280 kg ha^{-1} of fertilizer. The rate of peat moss, gypsum, calcium carbonate, rock phosphate and lake sediment had no significant effect on shoot biomass (Appendix E).

2.4.3.3 Root Biomass

As the rate of peat moss increased from 2 to 4 cm, root biomass significantly increased (F=0.0188). However, when peat moss was increased to 6 and 8 cm application rates no further significant increase to root biomass was observed (Table 2.7). Lake sediment applied at 10 cm significantly increased root biomass over 5 cm (F=0.0001). However, when lake sediment was increased to 15 cm, no significant increase in root biomass over the 10 cm rate was observed. The application rate of fertilizer, sewage sludge, gypsum, calcium carbonate and rock phosphate had no significant effect on root biomass (Appendix E).

2.4.3.4 Plant Height

Sewage sludge increase from 5 to 10 cm significantly increased plant height (F=0.0031). When sewage sludge was increased to 15 cm, plant height again significantly increased over the 10 cm application rate (F=0.0004) (Table 2.7). As lake sediment was increased from 5 to 10 cm, plant height significantly increased (F=0.0131). However, when lake sediment was increased to 15 cm, plant height did not significantly increase. When peat moss was increased from 2 to 4 cm, plant height was significantly increased (F=0.0392) (Table 2.7). When peat moss was raised to 6 and 8 cm no significant increase in plant height was observed. The rate of application of fertilizer, gypsum, calcium carbonate and rock phosphate had no significant effect on plant height.

2.4.4 Rate of Application Effect on Kimberlite Tailings Properties

2.4.4.1 Available Macronutrients

As sewage sludge increased from 5 to 10 cm, available N and S increased significantly (Table 2.8). When sewage sludge was further increased to 15 cm, N did not significantly increase, however, both available K and S significantly increased. Sewage sludge application rate had no effect on available P. As peat moss was increased, the availability of P, K and S were not significantly affected. However, peat moss rate increases from 2 to 4 cm (F=0.0005) and from 4 to 6 cm (F=0.0419) significantly increased available N (Table 2.8). Lake sediment increase from 5 to 10 cm significantly decreased available N (F=0.0029) and available P and K (Table 2.8). When lake sediment was increased to 15 cm, there was no significant decreases in available N or P, however, K and S continued to significantly decrease in availability. Fertilizer, gypsum, calcium carbonate and rock phosphate rates had no significant effect on availability of N, P, K or S with one exception. As gypsum rate was increased from 1086.5 to 3259.5 kg ha^{-1}, the amount of available S significantly increased.

2.4.4.2 Cation Exchange Capacity

CEC of the Ekati kimberlite tailings was affected by peat moss and lake sediment rates. As peat moss increased from 2 to 4 cm, CEC was significantly increased (F=0.0001). As peat moss increased from 4 to 6 cm and from 6 to 8 cm, CEC continued to increase significantly. Increased lake sediment rates resulted in a decreased CEC. As lake sediment rates rose from 5 to 10 cm and from 10 to 15 cm CEC significantly decreased for each amendment rate increase. The rates of sewage sludge, fertilizer, calcium carbonate, gypsum and rock phosphate had no significant effect on CEC (Appendix E).

2.4.4.3 Calcium, Magnesium Balance

Peat moss, lake sediment and gypsum rates significantly affected available calcium. As peat moss increased from 2 to 4 cm, 4 to 6 cm and 6 to 8 cm, available calcium significantly increased with each rate increase. Increases in lake sediment had the opposite effect, significantly decreasing available calcium. Lake sediment from 5 to 10 cm (F=0.0001) and from 10 to 15 cm (F=0.0001) resulted in a significant decrease in available calcium. As gypsum increased from 1086.5 to 3259.5 kg ha^{-1}, available

calcium significantly increased. Sewage sludge, fertilizer, calcium carbonate and rock phosphate rates had no significant effect on available calcium.

2.5 Discussion

2.5.1 Structure Improvement and Nutrient Provision

As hypothesized, the most favourable plant response to the amended kimberlite tailings occurred when both physical and nutrient limitations were simultaneously addressed. Peat moss and sewage sludge improved both physical structure and the availability of macronutrients, particularly nitrogen (Table 2.5). The amendment of low macronutrient availability in these tailings is important for positive initial plant response but also for sustained growth as a nutrient cycle is established. However, without good substrate structure, nutrients are lost to leaching or made unavailable to vegetation (Hausenbuiller 1985). Soil structure (the way particles are arranged together in a substrate) govern how water and air move in a substrate and fundamentally influence the suitability of a substrate for the growth of plants (Brady and Weil 1996).

The addition of N and P in previous studies resulted in favourable plant response (Miles and Tainton 1979a) and little or no growth was expected on kimberlite tailings without N and P additions. Results from this study are similar in that plant growth improved with N and P additions. However, ground cover and biomass were most favourably when structural improving and macronutrient providing amendments were combined. Good structure, including organic carbon creates a substrate that not only holds sufficient amounts of water and nutrients but also facilitates the availability of these essential elements to plants (Brady and Weil 1996). Ground cover and biomass are important growth parameters for stabilizing a substrate and therefore structural amendment of these kimberlite tailings will serve to better meet project objectives (Winterhalder 1992).

In creating a nutrient cycle the addition of N and P by fertilizer or sewage sludge is important in establishing a capital of macronutrients essential in system sustainability (Palmer 1987). A lack of N is cited as the major limiting factor in establishment of a nutrient cycle on disturbed lands. More specifically the balance of N and C must be right for effective microbial activity to occur. Without structural integrity substrate conditions will not facilitate the break down of organic additions and a nutrient cycle cannot exist.

Additions of calcium in gypsum, rock phosphate and calcium carbonate did not improve plant response or balance the Ca:Mg ratio. Studies suggest the benefit of surface applied gypsum may not show in the short term (Schuman et al. 1994). In a study on revegetation of mine spoil, perennial grass ground cover and biomass were not improved by the addition of surface applied gypsum until the third growing season. Schuman et al. (1994) suggested that time is required to dissolve the gypsum and cause any significant effect on plant growth. The 14-week growth period in this study was likely not sufficient to show the calcium addition effects, and further research would be needed to explore those effects.

2.5.2 Amendment Application Rates

With the exception of root biomass an increase in sewage sludge application resulted in increased plant growth. This is explained by the increased available macronutrients with increased sewage sludge application rate. The structural limitations of the tailings were also alleviated by sewage sludge, which increased available nutrients with increased application rate (Table 2.8). As sewage sludge was increased from 5 to 10 cm available N increased from 22.3 to 92.5 mg kg^{-1}. As the rate was further increased to 15 cm no further increase in available nutrients was observed (Table 2.8). Peat moss application at 2 cm provided N, P and K nutrient availability statistically equal to that provided by 8 cm suggesting that low amendment rates were sufficient for the tailings CEC limitations (Appendix E). This trend was similar with fertilizer application, which showed no increase in availability of macronutrients with increased rate, suggesting application rates

were too high and the nutrient holding capacity of the substrate was exceeded by even the low fertilizer application rates.

With the exception of lake sediment all amendment applications, despite rate, had either a beneficial or indifferent effect on the Ekati kimberlite tailings. Lake sediment, however, with increased rate caused plant growth properties to degrade reducing ground cover from 31% at 5 cm to 28% at 10cm to 22% at 15 cm (Table 2.7). As lake sediment increased available macronutrients (N, P, K, S), CEC and available calcium all significantly decreased which explains the poor performance of lake sediments in producing good plant growth response. The lack of organic carbon in this material is likely responsible for this decrease in nutrient availability and CEC (Campbell 1996). With a clay content of 15% it is surprising to see increased lake sediment decreasing CEC and available calcium as negatively charged clay particles should hold positively charged minerals in the substrate waiting for hydrogen ion displacement and plant uptake (Campbell 1996). Lake sediment if used in reclamation of these kimberlite tailings should be applied in reduced concentrations (less then 5 cm surface application) and combined with nutrient and organic carbon sources. Research by Kidd (1999) shows high iron concentrations in plant tissue grown in the Ekati lake sediment, which also supports reducing application rates. Lake sediment did show some promise in promoting high root biomass. Lake sediment should be further tested at reduced rates (< 5 cm) in combination with optimum rates of sewage sludge and peat moss.

In reclamation of these tailings, feasibility of amendment combinations, application methods and rates of application must be considered. Excessive application of amendments is not only costly but an inefficient use of resources. It is clear that rate of application of each of these test amendments will affect the success of the vegetation and should be further researched. Application rates of amendments in this study, with the exception of sewage sludge, were too high. Peat moss application at 2 cm resulted in 53% cover, at 4 cm 67% cover, at 6 cm 54% and at 8 cm 59% ground cover (Table 2.7). These results suggest that peat moss at 2 cm was sufficient as no significant increase in ground cover was observed with increased application rate. This trend was the same for

lake sediment suggesting, lesser quantities of peat moss and lake sediment should be tested to determine optimum application rates.

2.5.3 Amendment Recommendations

The remote nature of the Ekati Diamond Mine and its dewatered kimberlite tailings containment area raise the question of reclamation cost and overall amendment feasibility. Without permanent road access, cost of transporting materials to the mine by air is high. This study considered cost in initial amendment selection, however, application method and rate, availability and purchase cost of each amendment must be included in the overall feasibility of large-scale tailings reclamation. For overall feasibility, sewage sludge would be the best option, as it is produced at the mine and therefore requires low transport costs and no purchase cost. It was the most effective single amendment as a nutrient source and with proper safety procedures (section 2.3.2) could ultimately solve both sewage disposal and tailings nutrient availability issues.

Commercial peat moss performed well in ameliorating the Ekati kimberlite tailings structural limitations and would likely prove valuable as a long-term nutrient source if a nutrient cycle were successfully established. However, the cost associated with the purchase and transport of commercial peat moss will be high and based on rate of application performance should be tested at lower more feasible rates perhaps in combination with small amounts of lake sediment or papermill sludge. Papermill sludge has shown excellent potential and has proven beneficial on acid-generating tailings in other research (Belsito and Winterhalder 1999). Composted papermill sludge should be considered for further testing as a structure improving and long-term nutrient providing amendment for the Ekati kimberlite tailings. Although there will be transport costs, there is no purchase cost, making it a less expensive alternative to peat moss. In selecting a structure improving amendment for large-scale reclamation the balance between C and N must be considered. The mineralization of organically bound N is essential if a nutrient cycle is to be established and reclamation efforts are to be self-sustaining (Palmer 1987).

Further consideration of the C:N ratio in this research is made in the field study (Section 3.5.1).

The question to be considered now is how will these amendments perform in the harsh environment and high latitude of the Ekati Diamond Mine tailings containment area? A field study was conducted at the Ekati mine site on the Long Lake Tailings Containment Facility considering the performance of amendment combinations under field conditions. Amendments were evaluated over a two-year period considering both plant performance and substrate properties. The results of this field research are essential in justifying recommendations for large-scale reclamation by this study.

2.6 Conclusions

1. Plant growth was most favourable when both structural and nutrient limitations of the Ekati kimberlite tailings were simultaneously addressed.
2. Sewage sludge was the most effective single amendment in nutrient provision and as it is produced at the mine site seems the most efficient choice as a nutrient source.
3. Both peat moss and papermill sludge performed well, increasing water and nutrient holding capacities and overall tailings structure. Papermill sludge is recommended for further testing as cost of purchase would be much lower then peat moss and initial results suggest comparable performance.
4. Application rates of both structure improving and nutrient providing amendments were too high and further research investigating optimum rates in recommended.
5. Lake sediment resulted in a negative tailings property response, however, application rate was likely too high and further testing at reduced rates (< 5 cm) in combination with optimum rates of sewage sludge and peat moss is recommended.
6. Calcium additions did not raise the amount of total calcium in ameliorating the tailings serpentine state as hypothesized. However, continued monitoring of the field site could reveal long-term benefits of these additions.

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Table 2.1. Ekati processed kimberlite tailings substrate properties.

Properties	Ekati Processed Kimberlite
Available Calcium (meq 100 g^{-1})	17.1 (0.1)
Available Magnesium (meq 100 g^{-1})	17.7 (0.2)
Available Nitrate	1.8 (0.1)
Available Phosphate	10.5 (0.6)
Available Potassium	192.0 (6.7)
Available Sulphate	285.0 (18.4)
pH	8.0 (0.0)
Cation Exchange Capacity (meq 100 g^{-1})	2.0 (0.3)
Total Organic Carbon (%)	0.2 (0.0)
Sand Fraction (%)	82.9 (7.5)
Silt Fraction (%)	10.2 (1.1)
Clay Fraction (%)	6.9 (1.0)

Units are mg kg^{-1} unless otherwise noted

meg = millequivalents

Numbers in brackets represent the mean standard error between replicates

Table 2.2. Properties comparison of structural improving amendments.

Properties	Peat Moss	Lake Sediment	Sewage Sludge	Papermill Sludge	Agri-Boost
Moisture (%)	6	4	80	6.3	6.2
Total Carbon (%)	34	0.2	1.5	40	42
Available Ca (meg kg^{-1})	21	1.4	13	100	159
Available Mg (meg kg^{-1})	2	1.4	8	18	29
Available Nitrate (mg kg^{-1})	5	8	210	34	211
Available Phosphorus (mg kg^{-1})	3.3	116	30	34	70
Available Potassium (mg kg^{-1})	24	17	50	80	2350
Available Sulfate (mg kg^{-1})	25	>1	539	20	26
CEC (meq 100 g^{-1})	80	2	68	86	56
pH	4.2	7.7	6.6	7.4	6.2
Sand Fraction (%)		31			
Silt Fraction (%)		54			
Clay Fraction (%)		15			
Fecal Coliform (CFU dL^{-1})			6.8×10^6		
Fecal Streptococcus (CFU dL^{-1})			3.4×10^6		

CEC = cation exchange capacity

Table 2.3. Overall rank of amendment combinations based on plant response.

Amendment	Cover	Shoot	Root	Height	Total
PGCF	2	1	3	7	13
PSRG	3	4	2	4	13
SGR	9	5	4	2	20
PSRGF	5	2	6	10	23
PGRF	1	9	7	11	28
LS	18	8	1	3	30
LSGR	6	10	14	1	31
SC	8	6	16	5	35
PS	7	13	8	18	46
PSF	4	7	17	20	48
LSGRF	20	3	18	8	49
LGRF	13	14	13	12	52
RF	12	11	25	6	54
LF	15	12	15	15	57
PGC	10	19	9	19	57
LP	17	18	10	16	61
GF	11	16	22	14	63
GRF	16	15	26	9	66
LPGR	21	23	11	22	77
CF	19	21	19	21	80
LGR	22	25	5	28	80
LC	24	22	21	17	80
LPGRF	23	24	12	27	84
S	26	20	28	13	86
F	25	17	29	23	87
P	14	26	23	32	94
L	27	29	20	25	95
C	28	27	27	24	106
PGR	29	28	24	26	107
G	32	30	30	31	123
K (control)	30	31	32	30	123
GR	31	32	31	33	127
R	33	33	33	29	128

Amendment abbreviations (Appendix A, Table 1)
Statistical significance (Appendix E)

Table 2.4. Mean plant growth in the first greenhouse session.

Amendment	Cover (%)	Height (cm)	Shoot Biomass (g)	Root Biomass (g)
C	22 (1.8)	14.1 (1.2)	0.53 (0.03)	0.58 (0.05)
CF	38 (5.9)	16.0 (0.5)	0.79 (0.05)	0.81 (0.09)
F	27 (3.2)	15.6 (1.0)	0.87 (0.06)	0.47 (0.03)
G	14 (2.8)	11.6 (2.2)	0.35 (0.03)	0.35 (0.03)
GF	46 (6.3)	18.3 (1.2)	0.94 (0.04)	0.77 (0.08)
GR	15 (3.4)	11.0 (0.4)	0.26 (0.01)	0.30 (0.01)
GRF	42 (3.2)	19.1 (1.7)	0.95 (0.01)	0.59 (0.04)
K (control)	17 (1.9)	11.8 (0.8)	0.26 (0.01)	0.28 (0.02)
L	24 (2.1)	13.6 (0.7)	0.45 (0.01)	0.80 (0.07)
LC	30 (0.8)	17.8 (1.1)	0.73 (0.02)	0.80 (0.01)
LF	43 (6.4)	18.2 (0.5)	1.18 (0.06)	1.01 (0.08)
LGR	33 (1.2)	12.0 (0.3)	0.66 (0.01)	1.25 (0.10)
LGRF	45 (2.0)	18.8 (0.9)	1.11 (0.05)	1.07 (0.07)
LP	41 (5.5)	18.0 (1.6)	0.86 (0.04)	1.13 (0.07)
LPGR	35 (2.0)	15.8 (0.6)	0.71 (0.01)	1.12 (0.06)
LPGRF	30 (1.5)	13.4 (1.1)	0.71 (0.01)	1.12 (0.06)
LS	38 (1.5)	21.4 (0.7)	1.43 (0.05)	2.20 (0.20)
LSGR	53 (2.4)	27.8 (1.6)	1.38 (0.04)	1.03 (0.05)
LSGRF	35 (6.0)	19.8 (1.1)	1.59 (0.15)	0.85 (0.07)
P	45 (2.5)	11.6 (0.5)	0.62 (0.02)	0.76 (0.05)
PGC	50 (4.6)	16.5 (0.9)	0.83 (0.01)	1.21 (0.05)
PGCF	61 (4.3)	19.8 (0.8)	1.72 (0.08)	1.33 (0.02)
PGR	20 (1.5)	13.5 (1.2)	0.49 (0.03)	0.70 (0.06)
PGRF	62 (3.2)	18.9 (0.7)	1.41 (0.04)	1.23 (0.09)
PS	52 (3.2)	16.9 (0.7)	1.13 (0.03)	1.22 (0.08)
PSF	56 (2.4)	16.4 (0.9)	1.48 (0.04)	0.93 (0.01)
PSRG	60 (4.1)	21.3 (1.1)	1.58 (0.03)	1.59 (0.06)
PSRGF	56 (3.8)	19.1 (0.8)	1.66 (0.03)	1.24 (0.02)
R	11 (1.3)	11.9 (1.8)	0.23 (0.02)	0.26 (0.02)
RF	46 (3.1)	20.9 (1.7)	1.27 (0.09)	0.65 (0.02)
S	27 (3.9)	18.5 (1.2)	0.82 (0.02)	0.52 (0.01)
SC	51 (1.3)	21.0 (1.1)	1.54 (0.02)	0.97 (0.02)
SGR	51 (2.4)	24.1 (0.7)	1.58 (0.07)	1.31 (0.08)

Numbers in brackets represent the mean standard error
Amendment abbreviations (Appendix A, Table 1)
Statistical significance (Appendix E)

Table 2.5. Mean available nitrate, phosphorus, potassium and sulphate in the first greenhouse session (mg kg^{-1}).

Amendment	Nitrate	Phosphorus	Potassium	Sulphate
C	2.7 (0.4)	14.3 (2.3)	186 (6.8)	337 (89)
CF	4.6 (1.8)	37.3 (4.0)	196 (9.8)	261 (68)
F	2.4 (0.2)	34.0 (1.6)	176 (8.9)	252 (41)
G	1.9 (0.1)	11.0 (0.4)	216 (2.8)	566 (106)
GF	1.9 (0.1)	23.0 (1.6)	189 (6.9)	429 (72)
GR	2.3 (0.1)	14.3 (0.6)	210 (6.8)	1021 (61)
GRF	1.8 (0.2)	32.8 (2.4)	183 (5.7)	444 (81)
K (control)	1.8 (0.1)	10.5 (0.3)	192 (3.3)	285 (36)
L	1.9 (0.1)	11.8 (0.9)	159 (3.9)	168 (17)
LC	1.7 (0.1)	13.3 (1.1)	162 (4.9)	130 (23)
LF	2.0 (0.2)	41.8 (6.8)	156 (8.6)	36 (8)
LGR	1.7 (0.1)	11.3 (0.6)	137 (8.7)	298 (77)
LGRF	4.2 (0.6)	48.8 (4.7)	130 (4.9)	338 (57)
LP	1.9 (0.1)	11.0 (0.6)	133 (6.3)	88 (8)
LPGR	1.8 (0.1)	11.3 (0.5)	125 (7.9)	323 (74)
LPGRF	1.7 (0.1)	10.5 (0.5)	133 (4.9)	294 (46)
LS	1.7 (0.1)	16.0 (0.7)	130 (12.8)	178 (10)
LSGR	3.4 (0.7)	14.8 (1.0)	115 (5.2)	276 (70)
LSGRF	1.7 (0.1)	18.5 (3.1)	120 (8.1)	637 (99)
P	3.0 (0.8)	13.0 (1.7)	174 (9.7)	310 (105)
PGC	2.5 (0.4)	12.8 (0.5)	184 (7.9)	511 (118)
PGCF	1.8 (0.2)	57.5 (2.2)	181 (9.6)	692 (143)
PGR	2.4 (0.4)	13.5 (0.3)	237 (24.7)	479 (64)
PGRF	2.6 (0.2)	56.0 (5.4)	190 (8.3)	452 (51)
PS	10.5 (0.8)	23.8 (0.3)	168 (3.3)	368 (43)
PSF	3.2 (0.8)	41.0 (4.3)	186 (7.7)	394 (73)
PSRG	2.2 (0.1)	21.0 (0.7)	163 (8.3)	644 (107)
PSRGF	10.1 (1.8)	59.3 (1.0)	200 (14.1)	732 (103)
R	2.4 (0.2)	36.0 (3.7)	211 (5.6)	498 (76)
RF	1.9 (0.2)	13.3 (0.5)	186 (4.7)	236 (64)
S	2.5 (0.3)	16.5 (0.7)	190 (7.8)	539 (72)
SC	2.2 (0.1)	24.8 (2.1)	187 (3.5)	441 (33)
SGR	2.0 (0.1)	18.3 (0.3)	185 (3.7)	806 (80)

Numbers in brackets represent the mean standard error
Amendment abbreviations (Appendix A, Table 1)
Statistical significance (Appendix E)

Table 2.6. Mean substrate properties for the first greenhouse session.

Amendment	CEC (meq 100 g^{-1})	Total OC (%)	Available Ca (mg kg^{-1})	Available Mg (mg kg^{-1})
C	19.5 (0.18)	0.35 (0.06)	15.7 (0.16)	17.0 (0.37)
CF	19.9 (0.18)	0.23 (0.03)	16.5 (0.14)	16.9 (0.25)
F	20.5 (0.38)	0.45 (0.03)	15.4 (0.14)	17.1 (0.23)
G	20.3 (0.41)	0.35 (0.03)	18.4 (0.34)	17.2 (0.47)
GF	19.3 (0.29)	0.33 (0.03)	17.8 (0.27)	15.8 (0.13)
GR	20.9 (0.14)	0.25 (0.03)	21.5 (0.23)	17.3 (0.28)
GRF	20.5 (0.17)	0.40 (0.04)	17.1 (0.64)	15.4 (0.24)
K (control)	21.2 (0.33)	0.23 (0.03)	17.1 (0.09)	17.7 (0.24)
L	12.8 (0.55)	0.20 (0.00)	12.9 (0.34)	11.7 (0.38)
LC	15.8 (0.33)	0.18 (0.03)	14.9 (0.37)	14.1 (0.35)
LF	13.5 (0.74)	0.18 (0.03)	11.4 (0.35)	10.9 (0.50)
LGR	13.5 (0.23)	0.20 (0.00)	14.4 (0.46)	10.6 (0.27)
LGRF	14.8 (0.73)	0.20 (0.00)	15.5 (0.85)	11.1 (0.67)
LP	18.2 (0.62)	1.23 (0.10)	15.2 (0.51)	13.1 (0.40)
LPGR	19.2 (0.56)	1.33 (0.10)	18.0 (0.38)	12.3 (0.30)
LPGRF	19.3 (1.03)	1.23 (0.07)	17.6 (0.93)	13.0 (0.87)
LS	13.6 (0.54)	0.20 (0.00)	12.1 (0.21)	11.6 (0.37)
LSGR	13.4 (0.89)	0.15 (0.03)	14.0 (0.50)	9.7 (0.27)
LSGRF	13.7 (0.78)	0.10 (0.00)	14.9 (0.97)	10.7 (0.43)
P	23.9 (1.66)	1.03 (0.26)	18.5 (1.54)	17.6 (1.44)
PGC	24.4 (0.19)	1.55 (0.03)	21.1 (0.14)	17.9 (0.26)
PGCF	24.0 (0.50)	1.58 (0.09)	20.0 (0.54)	19.1 (0.66)
PGR	23.9 (0.35)	1.20 (0.30)	20.9 (0.65)	17.4 (0.36)
PGRF	23.9 (0.38)	1.35 (0.09)	20.1 (0.26)	16.8 (0.19)
PS	23.3 (0.31)	1.45 (0.06)	18.7 (0.32)	18.2 (0.11)
PSF	23.7 (0.25)	1.70 (0.07)	17.5 (0.41)	18.9 (0.39)
PSRG	23.7 (0.40)	1.53 (0.16)	19.4 (0.51)	17.4 (0.23)
PSRGF	23.2 (0.26)	1.58 (0.16)	20.0 (0.55)	17.4 (0.55)
R	20.4 (0.09)	0.38 (0.03)	17.9 (0.08)	17.4 (0.18)
RF	20.2 (0.24)	0.23 (0.03)	16.5 (0.30)	16.9 (0.29)
S	22.0 (0.54)	0.40 (0.00)	17.1 (0.45)	18.5 (0.41)
SC	22.3 (0.52)	0.40 (0.04)	17.2 (0.10)	19.9 (0.18)
SGR	22.7 (0.26)	0.38 (0.03)	20.3 (0.18)	19.3 (0.32)

Numbers in brackets represent the mean standard error
Amendment abbreviations (Appendix A, Table 1)
Statistical significance (Appendix E)

Table 2.7. Mean plant growth in the second greenhouse session.

Amendment	Cover (%)	Height (cm)	Shoot Biomass (g)	Root Biomass (g)
K (control)	22 (1.0)	7.8 (0.3)	0.73 (0.02)	1.29 (0.07)
P 2	41 (0.5)	9.5 (1.0)	0.91 (0.03)	1.05 (0.02)
P 4	42 (1.8)	11.1 (1.4)	0.76 (0.01)	1.19 (0.03)
P 6	50 (1.7)	10.0 (0.8)	1.01 (0.01)	1.96 (0.07)
P 8	54 (1.3)	9.6 (0.6)	1.09 (0.02)	3.01 (0.01)
L 5	31 (0.5)	8.4 (0.9)	0.66 (0.01)	1.64 (0.09)
L 10	27 (1.3)	7.5 (0.5)	0.58 (0.01)	1.26 (0.11)
L 15	25 (0.6)	6.8 (0.9)	0.51 (0.02)	0.69 (0.04)
S 5	28 (0.9)	16.5 (0.6)	1.13 (0.03)	2.13 (0.16)
S 10	48 (0.8)	17.3 (0.8)	2.09 (0.06)	2.16 (0.11)
S 15	70 (1.6)	18.0 (0.4)	1.92 (0.11)	2.14 (0.21)
GR	24 (0.5)	10.8 (1.3)	0.46 (0.03)	0.59 (0.06)
F	13 (1.5)	9.9 (1.6)	0.52 (0.06)	0.49 (0.08)
GRF	37 (0.5)	16.0 (0.8)	1.17 (0.03)	0.96 (0.04)
P2GR	13 (0.5)	10.3 (0.9)	0.36 (0.01)	0.61 (0.03)
P2F	53 (1.7)	16.0 (0.7)	1.36 (0.04)	1.26 (0.03)
P2GRF	35 (1.2)	12.4 (2.4)	1.01 (0.12)	0.91 (0.09)
P4GR	41 (0.8)	10.5 (1.0)	1.13 (0.07)	1.50 (0.04)
P4F	67 (0.8)	17.8 (1.7)	1.87 (0.04)	2.00 (0.12)
P4GRF	62 (2.6)	16.0 (1.1)	1.91 (0.08)	2.05 (0.13)
P6GR	28 (0.7)	12.1 (1.3)	0.78 (0.02)	1.85 (0.11)
P6F	54 (1.7)	13.3 (1.1)	1.15 (0.08)	2.23 (0.08)
P6GRF	44 (1.2)	13.8 (1.5)	1.13 (0.03)	0.94 (0.03)
P8GR	38 (1.2)	9.8 (0.6)	0.73 (0.04)	2.27 (0.21)
P8F	59 (1.0)	13.3 (0.9)	1.54 (0.06)	1.78 (0.12)
P8GRF	52 (2.2)	16.3 (1.3)	1.50 (0.06)	1.62 (0.08)
L5GR	31 (0.6)	11.4 (0.9)	2.76 (0.52)	2.14 (0.11)
L5F	26 (0.6)	12.9 (1.0)	0.86 (0.02)	1.29 (0.07)
L5GRF	20 (0.4)	14.1 (0.7)	0.82 (0.06)	0.71 (0.05)
L10GR	28 (1.1)	12.9 (0.7)	0.96 (0.05)	3.59 (0.21)
L10F	54 (1.8)	19.4 (0.9)	2.18 (0.06)	4.17 (0.16)
L10GRF	52 (1.9)	15.8 (0.8)	3.91 (0.57)	3.39 (0.31)
L15GR	22 (0.4)	13.0 (1.4)	0.77 (0.01)	2.38 (0.10)
L15F	48 (0.8)	22.3 (0.6)	2.64 (0.04)	3.84 (0.10)
L15GRF	63 (1.8)	14.8 (1.0)	1.68 (0.03)	3.26 (0.18)
S5GR	31 (0.8)	19.6 (0.2)	1.07 (0.08)	1.86 (0.06)
S5F	58 (1.6)	22.1 (1.4)	2.17 (0.09)	3.38 (0.26)
S5GRF	33 (0.6)	13.8 (1.9)	0.96 (0.07)	1.36 (0.11)
S10GR	32 (1.6)	16.8 (1.1)	1.25 (0.09)	2.09 (0.21)
S10F	20 (2.0)	12.6 (3.4)	0.67 (0.08)	0.72 (0.12)
S10GRF	32 (1.7)	14.0 (1.6)	1.24 (0.08)	1.30 (0.19)
S15GR	45 (1.5)	16.5 (1.5)	1.43 (0.06)	1.24 (0.06)
S15F	71 (1.4)	19.8 (1.0)	2.37 (0.07)	3.00 (0.31)
S15GRF	48 (0.8)	19.1 (1.4)	2.12 (0.03)	1.51 (0.08)

Numbers in brackets represent the mean standard error
Amendment abbreviations (Appendix A, Table 1)
Statistical significance (Appendix E)

Table 2.8. Mean available nitrate, phosphorus, potassium and sulphate in the second greenhouse session (mg kg^{-1}).

Amendment	Nitrate	Phosphorus	Potassium	Sulphate
F	61.5 (8.5)	61.3 (8.9)	207 (3.1)	709 (32)
GR	3.5 (1.8)	13.5 (0.6)	191 (4.6)	1145 (123)
GRF	21.0 (8.8)	62.0 (8.8)	194 (4.9)	901 (38)
K (control)	2.0 (0.0)	9.3 (0.3)	192 (2.1)	152 (68)
L10	1.8 (0.3)	8.0 (0.0)	114 (3.9)	162 (57)
L10F	2.5 (1.5)	108.5 (29.9)	101 (7.4)	322 (30)
L10GR	1.8 (0.8)	8.8 (0.5)	99 (4.5)	438 (22)
L10GRF	1.8 (0.9)	313.5 (133.9)	106 (1.4)	441 (18)
L15	2.0 (0.0)	7.8 (0.3)	106 (3.4)	219 (89)
L15F	9.8 (6.6)	67.3 (3.8)	79 (4.5)	273 (32)
L15GR	0.3 (0.3)	9.0 (1.4)	80 (4.8)	147 (49)
L15GRF	1.3 (0.9)	40.5 (3.3)	85 (9.4)	227 (60)
L5	1.8 (0.3)	8.3 (0.3)	161 (7.9)	123 (59)
L5F	31.5 (8.7)	33.5 (8.4)	133 (21.2)	362 (20)
L5GR	1.5 (0.5)	10.8 (1.3)	120 (1.1)	612 (48)
L5GRF	48.8 (18.3)	62.8 (4.1)	146 (8.8)	687 (89)
P2	2.5 (0.6)	10.3 (0.3)	194 (5.1)	190 (78)
P2F	18.0 (9.3)	39.3 (9.3)	173 (4.3)	920 (85)
P2GR	1.0 (0.0)	9.5 (0.6)	202 (13.1)	780 (84)
P2GRF	37.5 (9.8)	46.0 (0.8)	204 (11.7)	1251 (151)
P4	1.8 (0.3)	9.5 (0.3)	189 (4.5)	196 (79)
P4F	4.0 (2.04)	27.8 (4.5)	193 (6.4)	875 (45)
P4GR	1.0 (0.0)	9.0 (0.5)	182 (5.7)	889 (103)
P4GRF	1.0 (0.0)	24.0 (3.3)	179 (4.2)	846 (107)
P6	2.0 (0.4)	10.0 (0.4)	189 (3.4)	362 (152)
P6F	1.8 (0.5)	27.0 (1.1)	171 (6.2)	745 (68)
P6GR	1.0 (0.0)	9.3 (0.8)	175 (5.1)	1107 (114)
P6GRF	44.0 (13.6)	49.8 (3.4)	187 (7.9)	1365 (111)
P8	2.3 (0.3)	9.5 (0.3)	184 (2.9)	386 (172)
P8F	23.3 (9.9)	64.0 (5.4)	190 (6.8)	787 (15)
P8GR	2.8 (1.8)	12.8 (0.8)	168 (4.7)	1347 (124)
P8GRF	42.0 (15.0)	59.0 (5.8)	174 (12.4)	1225 (111)
S10	2.5 (0.5)	22.0 (1.1)	185 (5.6)	450 (79)
S10F	92.5 (14.8)	74.0 (18.1)	222 (2.8)	523 (9)
S10GR	6.5 (4.2)	25.3 (0.9)	196 (7.9)	844 (47)
S10GRF	59.3 (8.0)	52.0 (6.5)	199 (3.3)	719 (33)
S15	34.3 (3.4)	34.5 (1.2)	173 (3.8)	371 (53)
S15F	53.3 (16.4)	82.0 (9.8)	189 (9.0)	508 (46)
S15GR	23.0 (11.6)	38.5 (7.0)	188 (6.1)	661 (40)
S15GRF	55.5 (12.7)	88.0 (4.8)	193 (11.8)	541 (58)
S5	9.3 (2.9)	26.3 (1.1)	198 (2.1)	471 (66)
S5F	22.3 (13.8)	64.7 (15.4)	188 (7.7)	582 (12)
S5GR	7.8 (2.6)	24.3 (3.0)	198 (7.1)	1022 (88)
S5GRF	62.5 (16.3)	47.0 (8.3)	228 (7.0)	1014 (13)

Numbers in brackets represent the standard error; Statistical significance (Appendix E)
Amendment abbreviations (Appendix A, Table 1)

CHAPTER III. ESTABLISHEMENT OF A VEGETATION COVER ON KIMBERLITE MINE TAILINGS: FIELD STUDY

3.1 INTRODUCTION

The extraction of diamonds from kimberlitic materials is accompanied by the production of large quantities of kimberlite waste rock or tailings (Miles and Tainton 1979a). High volumes of kimberlite tailings are usually deposited in surface containment facilities, resulting in significant areas of land being covered by exposed kimberlite materials. With no protective surface cover and a large exposed surface area, dried kimberlite tailings have a high erosive potential, which can result in redeposition of tailings materials on the surrounding undisturbed lands. Stabilization of these waste materials is therefore a critical component of impact reduction. The most popular method of stabilizing tailings waste is with a vegetation cover. However, it can be difficult on kimberlite tailings as they often exhibit unsuitable substrate properties for plant colonization (Miles and Tainton 1979b, Cox and Hutchinson 1980).

Laboratory testing (Chapter 2) has shown coarse texture, no organic component, lack of available macronutrients and a serpentine state (Ca/Mg fraction 0.58) to be the principal limiting factors to plant growth on kimberlite mine tailings (Section 2.3.1). However, greenhouse research has shown that through additions of nutrient providing and structure improving amendments these limitations can be alleviated and substantial growth of native grass species is possible (Chapter 2).

Based on these initial greenhouse results a series of field experiments were established on the Ekati kimberlite mine tailings consolidated in Long Lake Containment Facility (LLCF) (Appendix A, Figure 3). This study investigated the stabilization of the Ekati kimberlite mine tailings with a vegetation cover, focusing on kimberlite substrate improvement in relation to plant growth as well as species tolerance to poor conditions. Both structural improving and nutrient providing amendments were tested in various combinations (Appendix A, Figure 4).

3.2 Objectives and Hypotheses

3.2.1 Objectives

The objective of this study was to evaluate plant and substrate response to potentially promising amendment combinations under field conditions facilitating the establishment of a permanent vegetation cover.

The specific objectives were:

1. To assess the effect of amendments on the Ekati kimberlite tailings substrate properties (available nitrogen (N), phosphorus (P), potassium (K) and sulphur (S), cation exchange capacity (CEC), total organic carbon, total calcium (Ca) and total magnesium (Mg)) under field conditions.
2. To assess the effect of amendments on the Ekati kimberlite tailings in relation to plant response (height, health, ground cover, root/shoot biomass) under field conditions.
3. To assess the growth performance of seven native grasses selected as potential reclamation species (*Arctagrostis latifolia*, *Calamagrostis canadensis, Poa glauca, Poa alpina, Deschampsia beringensis, Festuca rubra* and *Deschampsia caespitosa*) (Appendix C).

3.2.2 Hypotheses

1. The addition of nutrient providing amendments will significantly increase the amount of available macronutrients in the Ekati kimberlite tailings.
2. The addition of structural improving amendments will significantly increase the Ekati kimberlite tailings cation exchange capacity and organic carbon.
3. The most effective amendment combinations in relation to plant response will include both a structure improving amendment and a nutrient source.
4. The addition of sewage sludge will result in significant increases in plant growth.

5. The addition of calcium carbonate, gypsum or rock phosphate to the Ekati kimberlite tailings will raise the amount of total calcium in the substrate ameliorating the tailings serpentine state and establishing a more natural calcium, magnesium fraction of 2.
6. The revegetation of the Ekati processed kimberlite tailings dewatered in Long Lake Containment Facility, Cell B, will result in substrate stabilization, reducing erosion and the possibility of redeposition on the surrounding undisturbed tundra.

3.3 Materials and Methods

2.3.1 Site Description

Ekati™ Diamond Mine is located approximately 300 km north of Yellowknife and 200 km south of the Arctic Circle in the Canadian Northwest Territories (Appendix A, Figure 1). The mine is located in a heath tundra ecosystem, parented by Precambrian granite swept clean by glaciations of the last ice age. Boulder fields, sand eskers and countless lakes cover the landscape. The area receives approximately 160 mm of precipitation annually which almost exclusively falls between the months of July and October. Temperatures range between -40 and 25 °C with only four months having mean temperatures over 0 °C (Appendix B Table 1) (BHP Diamonds Inc. 1997).

The kimberlite tailings at Ekati™ Diamond Mine are pumped from the processing facility and deposited into the natural basin of Long Lake Containment Facility (LLCF), approximately 15 km away (Appendix A, Figure 2). LLCF was a sequence of headwater lakes that were excluded from the watershed by a series of frozen dams and divided into five containment cells (A through E) (Appendix A, Figure 3). In spring 2000 tailings at the most northerly end of LLCF had significantly consolidated, causing them to become unstable and highly susceptible to wind and water erosion.

3.3.2 Field Procedures

Field plots were established on the Ekati kimberlite tailings dewatered in LLCF, Cell B in spring 2000 (Appendix A, Figure 4). Both structural improving and nutrient providing amendment combinations were tested. Seven reclamation species [*Arctagrostis latifolia* (polar grass), *Calamagrostis canadensis* (bluejoint), *Poa glauca* (tundra bluegrass), *Poa alpina* (alpine bluegrass), *Deschampsia beringensis* (bering hairgrass), *Festuca rubra* (creeping red fescue) and *Deschampsia caespitosa* (tufted hairgrass)] were evaluated (Appendix C). For more detailed profiles of the kimberlite tailings properties and the amendments tested see sections 2.3.1 and 2.3.2 and Table 3.5.

Two plot sizes were used; small plots 2 x 2 m and species study plots 2 x 5 m (Appendix A, Figure 4). In the first field season (August 2000), plots were designed and established on the dewatered kimberlite tailings at the north end of LLCF (Appendix A, Figure 3). Small plots and species study plots were randomly designated for specific treatment applications (Appendix A, Figure 4).

Peat moss was applied by volume. Low peat moss rates of 4 cm were spread over the appropriate plots, hand raked level, and incorporated into 24 cm of tailings with a rototiller, creating a 28 cm deep tilled surface cover. Treatment areas not receiving peat moss were tilled to a depth of approximately 28 cm. Each plot was rototilled twice in opposite directions to ensure consistent mixing.

Lake sediment treatments were also applied by volume. Lake sediment was used alone and in combination with gypsum and rock phosphate to amend the coarse physical state of the tailings. Ten centimetres of lake sediment was applied then hand raked level and rototilled with 18 cm of tailings creating a tilled depth of approximately 28 cm.

The quantity of Ca to amend the serpentine conditions of the kimberlite tailings was based on the Ca:Mg ratio normally found in undisturbed tundra soils. Ca was applied as gypsum and rock phosphate to the species study plots at a rate of 2173 and 2080 kg ha^{-1}, respectively (Table 3.5). Ca was also applied as calcium carbonate to the small amendment plots at a rate of 1667 kg ha^{-1}. Ca sources of gypsum (20.0% Ca) and rock

phosphate (26.9% Ca) were applied by weight to produce a 1:1 ratio of Ca from each source. The calcium sources were mixed and spread evenly over each plot with a Red Devil Garden Drop Spreader then rototilled to a depth of 17 cm into the plot surface.

The plots receiving sewage sludge first received peat moss as outlined above. A 1 m buffer was established around each sewage sludge treatment plot to prevent contaminating neighbouring plots. Berms were then constructed with rakes, enclosing the 2 x 2 m area and creating a dish-like structure for the liquid sewage sludge. The sewage sludge application rate was measured by volume. Sewage sludge at a depth of 10 cm was poured into each bermed plot area and allowed to soak in overnight. The plot was rototilled to a 28 cm depth (25 to 30 cm) the next morning.

Once all treatments had been applied the plots were seeded. The seed mixture consisted of an equal representation of all seven native grass species (Appendix A, Table 1). Small plots were broadcast seeded at 40 kg ha^{-1}, combined with the 10-34-10-5 fertilizer at 280 kg ha^{-1} and ammonium nitrate at 75 kg ha^{-1}. The small plots were lightly hand raked to incorporate the seed and fertilizer into the surface then covered with a Curlex erosion blanket anchored to the kimberlite surface with 10 cm spikes to prevent surface erosion and amendment contamination among plots. In the species study plots, individual species were hand seeded at a 1 to 2 cm depth in randomly assigned rows. Three rows of each species running across all 4 treatment combinations were sown for a total of 21 seed rows (Appendix A, Figure 4). After seeding, fertilizer and ammonium nitrate were broadcast over each species study plot at 280 and 75 kg ha^{-1}, respectively. Application method and seeding rates were based on recommendations for cold soils (Kubanis 1982).

3.3.3 Field Measurements: Quantification of Plant Growth

Treatment effectiveness was based on general plant health, plant development (tillering, flowering), vegetation cover (ground and row if hand seeded), plant height and shoot biomass. Biomass was measured in year 2 only, due to the destructive nature of this sampling method. A 0.5 m buffer around each small plot was not sampled to remove the

edge effect from neighbouring treatments. A 1 x 1 m area in the centre of the small plots was randomly sampled three times using a 20 x 50 cm quadrat. In the species study plots, random positions along the seeded rows were selected for assessment using a 20 x 50 cm quadrat. The first assessment was completed at the end of August 2000 and the second in August 2001.

Mean plant height was estimated based on all individuals rooted within the quadrat and maximum plant height was the height of the tallest individual. Overall plant health for individuals within each quadrat was based on a 4-point scale. Quadrats containing greater than 50% dead individuals were assessed a health value of 1; pots with 25 to 50% dead individuals were given a 2; quadrats with 5 to 25% dead individuals were given a 3; and quadrats with green robust cover and less then 5% dead individuals were assessed a 4 on the health scale. Flowering and tillering were also noted for individuals within each quadrat. Ground cover was estimated as a percent of the total area of each plot covered by vegetation. Biomass was measured, for both small and species study plots, by randomly placing the 20 x 50 cm quadrat within each plot and clipping all vegetation rooted inside the quadrat. The shoot biomass was then dried and weighed.

3.3.4 Soil Analyses

Soil was sampled randomly in the small field plots at depth increments of 0 to 10, 10 to 20, 20 to 30 and 30 to 60 cm for both 2000 and 2001 seasons. Samples were sent to EnviroTest Laboratories in Edmonton, Alberta for analysis. Each sample was analysed for the following: available nutrients (N, P, K and S), pH, total cations (Ca, Mg, Na and K), CEC, extractable cations, total carbon and total inorganic carbon. Available P and K were determined using a modification of the Kelowna Extraction method (Qian et al. 1994). Available N and S were determined by a calcium chloride extraction method (Carter 1993). Substrate pH was measured using a saturated soil paste method (McKeague 1978). Total cations were determined by a saturated paste method (Carter 1993). CEC and extractable cations were both determined by the NH_4O ammonium acetate extraction method (McKeague 1978). Total carbon was determined using a Leco

Furnace combustion method (Carter 1993). Total inorganic carbon was determined by dilution with hydrochloric acid (Carter 1993). Total organic carbon was calculated from the difference between total carbon and total inorganic carbon.

3.3.5 Experimental Design

The study used a complete block design replicated three times. The 9 small plot amendment combinations included: (rock phosphate, lake sediment + gypsum + rock phosphate, lake sediment, high peat moss + sewage sludge + rock phosphate + gypsum, calcium carbonate, gypsum, high peat moss + gypsum + calcium carbonate, high peat moss + gypsum). Each treatment was replicated 3 times for a total of 27 small plots (Appendix A, Figure 4). In the species study plots individual species were seeded in randomly assigned rows across the following treatments: 2 peat moss amendments (low peat moss 4 cm, no peat moss) x 2 calcium amendments (gypsum + rock phosphate, no calcium) = 4 treatments. Each species was seeded in three separate rows: 7 species x 3 replicates = 21 seeded rows across all treatments (Appendix A, Figure 4).

3.3.6 Statistical Analyses

Orthogonal contrasts were used to compare the means of grouped treatments (Petersen 1994). This method allows the effect of each amendment to be considered for each plant parameter. Using orthogonal contrasts all amendment combinations containing a given amendment (e.g. sewage sludge) could be grouped and compared to all other amendment combinations (e.g. not containing sewage sludge). The means of these two groups were compared in a linear function testing the hypothesis that the contrast is zero against the contrast statement not equalling zero. If the contrast statement does not equal zero it indicates the amendment groupings are significantly different. This statistical method can also be used to isolate amendment effects within a combination series (Petersen 1994). Duncan's Multiple Range test was used to make overall amendment comparisons. T-tests were used to make more specific comparisons between individual amendment combinations.

3.4 Results

3.4.1 Amendment Effect on Plant Growth

Sewage sludge significantly improved plant growth and when applied in combination with peat moss, gypsum and rock phosphate, producing 32% ground cover in the first growing season (Table 3.2). Lake sediment also performed well in this first field season producing plant cover of 38% when combined with a Ca source (Table 3.1). All three Ca sources had no significant effect on plant growth in either of the two field seasons. Results from the second growing season were similar to those of the first with sewage sludge and peat moss resulting in a 66% increase in ground cover over the unamended control and a shoot biomass production 336 g m^{-2} (Table 3.2) (Appendix C, Figure 1). Lake sediment did not perform as well in the second season and ground cover on lake sediment plots dropped from 38 to 22% (Tables 3.1 and 3.2).

3.4.1.1 Ground Cover

In the first field season ground cover (32%) was significantly increased by sewage sludge (F=0.0003), which was applied in combination with peat moss, gypsum and rock phosphate (Table 3.1). The highest ground cover was produced by lake sediment, gypsum and rock phosphate, at 38% (Table 3.1). Lake sediment alone performed well with a mean ground cover of 33% (F=0.0001) (Table 3.1). Peat moss significantly improved ground cover (F=0.0792). In comparing individual amendments lake sediment significantly out performed peat moss (F=0.0001) but was not significantly different from sewage sludge (F=0.3947) (Appendix E). In the second field season lake sediment was not as effective (F=0.2631) and the highest ground cover was produced by the sewage sludge, peat moss, gypsum and rock phosphate treatment at 70% (Table 3.2). Sewage sludge and peat moss combined significantly increased ground cover (F=0.0001) (Appendix C, Figure 1). None of the three Ca sources had any significant effect on ground cover in either field season (Tables 3.1 and 3.2).

3.4.1.2 Plant Height

In the first field season sewage sludge, peat moss or lake sediment significantly increased plant height (Table 3.1). The most successful amendment combination was sewage sludge, peat moss, gypsum and rock phosphate in combination with a plant height of 3.9 cm (Table 3.1). The tallest plants (11.9 cm) occurred on sewage sludge, peat moss, gypsum and rock phosphate. These individuals were almost twice as tall as the next most effective amendment combination of lake sediment, gypsum and rock phosphate (6.7 cm) (Table 3.1) (Appendix E). In the second field season sewage sludge, peat moss or lake sediment significantly affected plant height. Plants on plots with lake sediment did not perform as well in the second growing season (Appendix E). None of the three Ca sources had any significant effect on mean or maximum plant height in either growing season.

3.4.1.3 Shoot Biomass

Shoot biomass was only measured in the second growing season and as expected the sewage sludge, peat moss, gypsum and rock phosphate treatment out performed all others producing a mean shoot biomass of 336.2 g m^{-2} (Table 3.2). The next most favourable amendment in producing high biomass was lake sediment, gypsum and rock phosphate at 129.4 g m^{-2} (Table 3.2). Sewage sludge, peat moss or lake sediment significantly increased shoot biomass with sewage sludge out performing lake sediment and peat moss. None of the three Ca sources had any significant effect on shoot biomass.

3.4.2 Amendment Effect on Kimberlite Tailings Properties

3.4.2.1 Available Macronutrients

Sewage sludge significantly increased available N at 10 to 20 cm and 20 to 30 cm depths resulting in the highest available N levels observed in the field study, 45 and 54 mg kg^{-1}, respectively (Table 3.3). Peat moss significantly increased available N at 10 to 20 cm and 20 to 30 cm. In general the availability of N increased with depth in the tailings and the highest available N levels were found in the sewage sludge, peat moss, gypsum and rock phosphate treatment at 20 to 30 cm. The availability of P was significantly affected by sewage sludge (F=0.0001), increasing at all depth increments. Peat moss significantly

increased P availability at 0 to 10 cm (F=0.0001) and 20 to 30 cm (F=0.0075) but not at 10 to 20 cm (F=0.2449). No other amendments significantly affected P availability. The field availability of K and S was not significantly affected by any amendments.

3.4.2.2 Cation Exchange Capacity and Percent Organic Carbon

CEC was significantly improved by peat moss at 10 to 20 cm (F=0.0001) and 20 to 30 cm (F=0.0006) but not at 0 to 10 cm (F=0.2349). CEC was significantly decreased by lake sediment at 10 to 20 cm (F=0.0001) and at 20-30 cm (F=0.0070). The most favourable amendment combination in relation to CEC was peat moss and gypsum combined with a CEC of 20.36 meq 100 g^{-1} (Table 3.4) (Appendix E). Sewage sludge increased CEC, however, only at 20 to 30 cm was this increase significant (F=0.0074) (Table 3.4). None of the Ca sources significantly affected CEC. Organic carbon was significantly increased by sewage sludge and peat moss at all depths (Table 3.4).

3.4.2.3 Calcium, Magnesium Balance

The fraction of extractable calcium to magnesium was not significantly improved by any amendment. Peat moss and gypsum in combination raised the available calcium level to 22.6 meq 100 g^{-1}, the highest of any combination. However, this did not result in a significant improvement in the calcium magnesium fraction, which was 1.09 (Ca = 22.6 meq 100 g^{-1}, Mg = 20.7 meq 100 g^{-1}).

3.4.3 Plant Species Performance

In the first growing season there was very little growth on the species study plots with no significant difference between species or kimberlite amendments (Table 3.6). Bering hairgrass, tufted hairgrass and creeping red fescue performed the best in this first season with the fescue producing the highest ground cover (1.5%) (Table 3.6). In the second growing season a significant difference was observed among kimberlite amendments. Peat moss significantly improved plant growth over amendment combinations without peat moss (F = 0.0001) (Table 3.7 and 3.8). Calcium had no significant effect on plant growth (F = 0.1765). In the second growing season bering hairgrass was most successful

producing 53% cover and 213.6 g m^{-2} of shoot biomass on peat moss amended plots. Creeping red fescue also performed well with high ground cover (33%) and biomass (168,3 g m^{-2}) on peat moss amended plots (Table 3.6). The performance of creeping red fescue was not reduced as dramatically as the bering hairgrass without peat moss (Tables 3.6 and 3.7). The creeping red fescue lost 7% cover and 51.7 g m^{-2} of biomass while bering hairgrass lost 35% cover and 125.8 g m^{-2} biomass.

3.5 Discussion

Field research supported greenhouse results showing that low available macronutrients and poor substrate structure of the Ekati kimberlite tailings are critical limitations to plant establishment and development. As hypothesized, plant growth in the field was most successful when both structural limitations and nutrient deficiencies were improved. Sewage sludge and peat moss in combination provided significant improvements to tailings structure, increasing nutrient availability and resulting in the most successful ground cover, plant development and biomass production. Nutrient additions without structural improvements showed poor plant response and resulted in available nutrients concentrating deep in the tailings profile (30 to 60 cm). Without organic carbon nutrients may leached deeper within the profile and washed out of the rooting zone (Brady and Weil 1996). Lake sediment without nutrient provision resulted in good initial plant response (33% cover) but by the second growing season growth had significantly decreased, further supporting the hypothesis that both structure improvement and nutrient provision will be critical in establishing a sustainable vegetation cover on these kimberlite tailings. Without a capital of nutrients cycling cannot occur, therefore initial nutrient additions will be essential for the systems self-sustainability (Brady and Weil 1996).

Ca sources had no significant effect on plant response or substrate properties over two growing seasons as in the greenhouse. Research on plant response to gypsum additions on sodic mine spoil suggest that growth (cover and biomass) is not significantly affected

until the third growing season illustrating the time required for the gypsum to dissolve and become an effective soil nutrient (Schuman et al. 1994). In this study the site received an average annual precipitation of 362 mm compared to the annual precipitation at the Ekati mine site of below 160 mm. It is likely that low precipitation combined with latitude and short growing season will further extend the time required for the calcium sources to show significant results (BHP Diamonds Inc. 1997).

The availability of N and P in the rooting zone is considered the most common limiting factor to plant growth on coarse-textured substrates (Foth 1978). On the Ekati kimberlite tailings this follows with the most successful field amendment combination of sewage sludge, peat moss, gypsum and rock phosphate providing available N 20 times that of fertilized treatments as well as sufficient organic carbon to hold these nutrients and facilitate their uptake. This sewage sludge and peat moss combination maintained these available nitrate levels through the second growing season at a 10 to 20 cm depth (Table 3.3). The excellent performance of the sewage sludge may, however, be overshadowed by the associated risks of using biosolid waste materials as soil amendments (Bresson et al. 2001). The high fecal coliform (6.8×10^6 CFU dL^{-1}) and streptococcus (3.4×10^6 CFU dL^{-1}) levels in the Ekati sewage sludge may deter its use as a large-scale reclamation amendment. Research on coliform survival in surface applied sewage sludge suggests the health threats posed by coliform levels are temporary as survival is quickly reduced with time (Edmonds 1976) (Section 1.3.1). Edmonds (1976) shows that 64 days after sewage sludge application, in summer, coliform levels are reduced by almost 80% of original levels and after 200 days are less than 1% of application levels. With winter application the rate of survival is even more reduced and Edmonds shows that after only 162 days 0.02% of the original coliform levels are present and after 343 days 0% remain. For Ekati this translates to 1360 CFU dL^{-1} after 162 days, which is well below the US Code of Federal Regulations for waste discharge, which recommends 200 CFU 100 ml^{-1} (Dunigan and Dick 1980).

In this field research sewage sludge and peat moss in combination out performed all other amendment combinations in almost all quantified parameters and considering feasibility,

would be recommended for further testing on a larger scale. Lake sediment performed well, however, a reduction in positive vegetation response in the second season as well as poor performance in the greenhouse study suggests further exploration into the effects of lake sediment are required. The fine textured lake sediment was hypothesised to improve the tailings structure increasing water and nutrient holding capacities, however, this was not observed in either the field of greenhouse studies. In fact lake sediment with increased rate reduced CEC. The results of the field research suggest lake sediment will not sustain acceptable plant growth over time.

Monitoring of the field research plots should continue considering the effects of Ca have not yet been observed and self-sustainability can not be sufficiently studied in two growing seasons. Amendment additions to these dewatered kimberlite tailings have yielded encouraging results and when both structural and nutrient limitations are dealt with plant growth sufficient to stabilize this substrate is feasible.

In considering plant species as potential candidates for large-scale reclamation, both *Festuca rubra* and *Deschampsia beringensis* performed well. Both of these species were selected based on their native origins, their reputation for tolerance to low-fertility regimes and their associated ability to survive on highly disturbed sites at northern latitudes (Mitchell 1986). *Festuca rubra*, a common wetland Arctic species, is found throughout the circumpolar Arctic region (Kidd 1999). At more southern latitudes this species can present an invasive threat, however, at its natural latitude it is a common and important component of many riparian plant systems (Kidd 1999). Bering hairgrass is also known for its sustainability on disturbed sites and is commonly referred to as good low maintenance ground cover species (Mitchell 1986).

In the interest of promoting migration and colonization of native species from the surrounding undisturbed tundra, all species except polar grass, which did not grow on the Ekati tailings, are recommended for use in the reclamation seed mix. Studies on succession in tundra reclamation suggest that the higher the diversity of natives used in reclamation seed mixtures the higher the incidence of colonization from surrounding

undisturbed areas resulting in a more natural successional path for reclaimed sites (Cargill and Chapin 1987).

3.5.1 Carbon and Nitrogen Additions

In considering the long-term effects of adding amendments to the Ekati kimberlite tailings a closer evaluation of C and N must be made. If a self-sustaining vegetation cover is to be established conditions for the mineralization of N must be considered. Palmer (1987) states that the major limiting factor to nutrient cycling on disturbed lands is a lack of N. N is often bound in organic compounds of high C:N ratio or immobilized in microbial biomass. In such situations the C:N ratio in organic matter is too high for microorganisms to perform decomposition and any available N is quickly taken up and immobilized (Palmer 1987). Results from Reeder and Berg (1977) illustrate how substrate availability of ammonium and pH fluctuation affects microbial activity and consequently the availability of N to vegetation. If a nutrient cycle is to be established there has to be a steady supply of ammonium and/or nitrate and the pH has to be high enough for nitrification to take place (Reeder and Berg 1977). The pH of the Ekati kimberlite tailings is 8 and should not be a factor in nitrification. However, the C:N ratio of amendments is an important factor.

Microorganisms need about 24 parts C for every part N assimilated into their bodies (Brady and Weil 1996). If the C:N ratio of organic material added to a substrate is higher then 25:1 the soil microorganisms will scavenge the soil solution for N reducing its availability to vegetation (Brady and Weil 1996). Peat moss and papermill sludge were added as organic amendments and both had C:N ratios >25:1 (Table 3.9). The addition of these materials will initially limit N, however with time N will be mineralized as C breaks down improving the C:N ratio for microbial activity. It was shown that these organic amendments performed best when combined with a nutrient source (fertilizer + ammonium nitrate or sewage sludge). The peat moss C:N ratio when combined with fertilizer + ammonium nitrate was lowered to 27:1 resulting in a more favourable C:N balance. The most favourable amendment combination in this field study was peat moss

combined with sewage sludge and fertilizer. This combination had a C:N ratio of 23:1. N and P added to the tailings by the sewage sludge, peat moss and fertilizer combination totalled 1400 kg ha^{-1} N (available N 263 kg ha^{-1}) and 228 kg ha^{-1} P (Table 3.9). Plant biomass on this amendment was 3362 kg ha^{-1} taking up 38 kg ha^{-1} N and 4 kg ha^{-1} P, leaving 1362 kg ha^{-1} N and 224 kg ha^{-1} P in the tailings bound in organic matter and microbial biomass. The levels of P pose some environmental concerns and may restrict the application rates of P rich amendments like sewage sludge and lake sediment (Table 3.9). Sampling 4 and 16 months after amendment additions showed no excess mineral N in any field study plots. This suggests that available N not bound in organic matter or microbial biomass has leached out of the sampling area. The addition of organic matter to improve substrate structure must be matched with appropriate levels of N if amendments are to be efficiently utilized and long-term vegetation success is to be achieved.

3.6 CONCLUSIONS

1. Plant growth under field conditions was most favourable when both structural and nutrient limitation of the Ekati kimberlite tailings were simultaneously addressed.
2. Peat moss performed well increasing water and nutrient holding capacities and overall tailings structure.
3. Sewage sludge was the most effective amendment in nutrient provision and combined with peat moss produced the most favourable plant response.
4. Lake sediment showed promising initial plant growth but in only two seasons started to show a negative tailings property response, and subsequent reduced plant growth. Lake sediment should be further tested at reduced rates (< 5 cm) in combination with an organic carbon source (peat moss, papermill sludge) and a nutrient source (sewage sludge).
5. Ca did not raise the amount of total Ca in ameliorating the tailings serpentine state as hypothesized. However, continued monitoring of field plots could reveal long-term benefits.

6. *Festuca rubra* and *Deschampsia beringensis* produced the best plant growth response. However, all species except *Arctagrostis latifolia* performed well and are recommended for use in the Ekati native reclamation seed mix.

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Table 3.1. Mean plant growth in the first field season.

Amendment	Cover (%)	Mean Height (cm)	Max Height (cm)
Control	4 (1)	3.8 (0.3)	4.7 (0.5)
C	4 (2)	0.6 (0.1)	2.1 (0.2)
G	4 (1)	0.7 (0.1)	2.5 (0.3)
L	33 (6)	1.9 (0.3)	4.8 (0.4)
LGR	38 (4)	2.8 (0.3)	6.7 (0.8)
PG	17 (2)	1.8 (0.5)	5.1 (0.8)
PGC	16 (2)	1.7 (0.2)	3.9 (0.3)
PSRG	32 (5)	3.9 (0.4)	11.9 (1.5)
R	6 (2)	1.5 (0.5)	3.5 (0.8)

Numbers in brackets represent the mean standard error
Amendment abbreviations (Appendix A, Table 1)
Statistical significance (Appendix E)

Table 3.2. Mean plant growth in the second field season.

Amendment	Cover (%)	Mean Height (cm)	Max Height (cm)	Shoot Biomass ($g\ m^{-2}$)
Control	4 (2)	12.4 (2.2)	20.3 (4.8)	21.2 (14.4)
C	4 (1)	9.6 (1.4)	21.0 (3.3)	26.8 (13.8)
G	2 (1)	4.5 (1.6)	8.7 (3.2)	5.3 (2.7)
L	18 (2)	22.7 (1.3)	39.2 (1.5)	112.8 (39.1)
LGR	22 (4)	24.9 (1.5)	43.3 (1.8)	129.4 (10.7)
PG	8 (2)	17.9 (1.0)	34.4 (1.8)	45.5 (27.2)
PGC	13 (3)	16.9 (1.3)	36.3 (3.0)	84.3 (32.4)
PSRG	70 (12)	42.6 (5.8)	61.8 (7.4)	336.2 (88.1)
R	3 (1)	8.3 (2.1)	16.1 (4.2)	16.2 (7.5)

Numbers in brackets represent the mean standard error
Amendment abbreviations (Appendix A, Table 1)
Statistical significance (Appendix E)

Table 3.3. Mean available nitrogen, phosphorus, potassium and sulphur in the second field season (mg kg^{-1}).

Amendment	Depth (cm)	Nitrogen	Phosphorus	Potassium	Sulphur
C	0-10	1.7 (0.1)	28.7 (4.6)	185 (18)	215 (52)
C	10-20	2.3 (0.1)	9.0 (0)	212 (26)	513 (150)
C	20-30	3.4 (0.2)	10.0 (0.9)	198 (10)	414 (41)
G	0-10	1.1 (0.1)	28.0 (5.3)	171 (12)	322 (374)
G	10-20	1.3 (0.2)	10.0 (0.9)	205 (10)	481 (287)
G	20-30	1.8 (0.1)	7.7 (0.9)	185 (22)	647 (92)
L	0-10	1.7 (0.3)	20.3 (3.8)	147 (8)	754 (247)
L	10-20	0.8 (0.1)	12.0 (2.2)	145 (11)	775 (115)
L	20-30	0.8 (0.1)	8.7 (1.2)	166 (15)	765 (153)
LGR	0-10	0.9 (0.1)	19.0 (2.6)	144 (14)	827 (216)
LGR	10-20	0.7 (0.0)	10.3 (1.0)	137 (18)	906 (193)
LGR	20-30	0.9 (0.1)	8.0 (0.8)	149 (16)	712 (146)
PG	0-10	0.9 (0.1)	27.0 (5.6)	192 (11)	694 (154)
PG	10-20	1.0 (0.1)	9.7 (0.9)	219 (24)	1129 (136)
PG	20-30	1.2 (0.2)	9.3 (0.9)	209 (25)	1001 (190)
PGC	0-10	1.8 (0.2)	26.7 (2.3)	171 (10)	808 (277)
PGC	10-20	1.3 (0.3)	11.3 (0.9)	186 (14)	899 (241)
PGC	20-30	1.5 (0.2)	10.0 (1.1)	176 (13)	901 (105)
PSRG	0-10	14.3 (3.3)	140.7 (14.8)	193 (4)	904 (193)
PSRG	10-20	44.9 (11)	77.0 (11.2)	170 (28)	822 (305)
PSRG	20-30	54.1 (23)	38.7 (6.3)	195 (24)	849 (178)
R	0-10	0.9 (0.1)	19.7 (4.8)	181 (29)	509 (238)
R	10-20	0.9 (0.1)	8.3 (2.6)	157 (24)	361 (182)
R	20-30	1.2 (0.2)	8.0 (2.4)	156 (18)	432 (176)

Numbers in brackets represent the mean standard error
Amendment abbreviations (Appendix A, Table 1)
Statistical significance (Appendix E)

Table 3.4. Mean substrate properties for the second field season.

Amendment	Depth (cm)	Available Ca (meq 100 g^{-1})	Available Mg (meq 100 g^{-1})	CEC (meq 100 g^{-1})	Total OC (%)
C	0-10	14.7 (1.3)	13.8 (0.8)	15.9 (1.1)	0.33 (0.1)
C	10-20	16.7 (1.6)	17.6 (1.6)	18.1 (1.8)	0.44 (0.1)
C	20-30	15.3 (1.2)	17.2 (0.3)	16.8 (2.0)	0.26 (0.1)
G	0-10	17.1 (2.2)	13.5 (1.7)	15.1 (1.4)	0.27 (0.1)
G	10-20	16.7 (1.8)	16.9 (1.1)	17.1 (2.1)	0.33 (0.1)
G	20-30	14.8 (1.3)	17.0 (1.4)	16.0 (1.8)	0.32 (0.0)
L	0-10	15.4 (1.4)	13.2 (2.4)	12.4 (0.9)	0.17 (0.0)
L	10-20	13.7 (1.2)	14.4 (3.8)	10.4 (0.8)	0.14 (0.0)
L	20-30	15.2 (1.5)	17.4 (3.3)	13.7 (0.7)	0.20 (0.0)
LGR	0-10	16.8 (2.8)	12.7 (2.2)	12.0 (0.8)	0.10 (0.0)
LGR	10-20	14.0 (2.6)	12.6 (2.5)	9.1 (0.5)	0.07 (0.0)
LGR	20-30	13.8 (1.3)	15.0 (3.3)	11.9 (1.1)	0.17 (0.1)
PG	0-10	18.7 (0.6)	15.5 (0.8)	17.1 (1.2)	0.73 (0.2)
PG	10-20	22.6 (0.5)	20.7 (1.2)	23.4 (2.4)	1.73 (0.3)
PG	20-30	19.3 (0.4)	19.2 (0.6)	20.6 (2.2)	1.23 (0.3)
PGC	0-10	18.3 (1.6)	14.9 (3.8)	16.6 (1.8)	0.83 (0.1)
PGC	10-20	20.2 (2.1)	19.2 (4.2)	21.9 (2.2)	1.70 (0.2)
PGC	20-30	17.9 (1.4)	18.1 (3.4)	18.4 (2.1)	1.10 (0.1)
PSRG	0-10	19.4 (0.7)	15.9 (0.8)	14.7 (1.6)	1.10 (0.1)
PSRG	10-20	18.4 (1.3)	17.6 (3.2)	18.4 (1.6)	1.83 (0.3)
PSRG	20-30	20.7 (0.8)	20.1 (0.7)	22.7 (2.2)	1.77 (0.3)
R	0-10	17.8 (2.5)	14.8 (3.4)	15.2 (3.8)	0.14 (0.1)
R	10-20	14.8 (1.6)	14.6 (3.7)	13.6 (3.7)	0.10 (0.0)
R	20-30	13.8 (1.3)	15.2 (3.3)	13.7 (2.6)	0.13 (0.0)

Numbers in brackets represent the mean standard error
Amendment abbreviations (Appendix A, Table 1)
Statistical significance (Appendix E)

Table 3.5. Field study amendment application rates.

Amendment	Benefit to Kimberlite Tailings	Application Rate
Low Peat Moss 4 cm cover	A source of organics, improves substrate structure, lowers pH, increases water/nutrient holding capacity, prevents compaction, reduces erosion, provides nutrient source, and microorganisms.	400 m^3 ha^{-1}
High Peat Moss 8 cm cover	Higher level of organics, improves substrate structure, lowers pH, increases water/nutrient holding capacity, prevents compaction, reduces erosion, provides nutrient source, and microorganisms.	800 m^3 ha^{-1}
Lake Sediment 10 cm cover	Fine particulate improves substrate texture, improves water/nutrient holding capacity, dilutes kimberlite.	1 000 m^3 ha^{-1}
Sewage Sludge 10 cm cover	Provides some organic solids, improves substrate structure, inoculates substrate with microbial population, provides nutrients, aids in initiation of nutrient cycle.	1 000 m^3 ha^{-1}
Calcium Sulphate $CaSO_4$ Gypsum	Calcium source improves the Ca:Mg ratio, improves the serpentine conditions, immediate source of calcium.	2173 kg ha^{-1}
Granulated Rock Phosphate	Calcium source improves the Ca:Mg ratio, improves serpentine conditions, long-term source of calcium and phosphorus.	2080 kg ha^{-1}
Calcium Carbonate $CaCO_3$	Calcium source improves Ca:Mg ratio, improves serpentine conditions, long-term source of calcium.	1667 kg ha^{-1}
10-34-10-5 Fertilizer	Provides essential macronutrients for successful plant growth.	Drill 100 kg ha^{-1} Broadcast 280 kg ha^{-1}
Ammonium Nitrate 33-0-0	Increases nitrogen in substrate, essential for plant growth, initiation of nutrient cycle.	Drill 25 kg ha^{-1} Broadcast 75 kg ha^{-1}
Perennial Seed Mix	Provides substrate with long-term seed source for plant development, crop will aid in stabilizing substrate and allow for natural colonization.	Drill 20 kg ha^{-1} Broadcast 40 kg ha^{-1}
Annual Seed Mix	Provides substrate with seed source for plant development, crop will aid in stabilizing the substrate and allow for natural colonization.	Drill 130 kg ha^{-1}
Curlex Erosion Blanket	Stabilizes kimberlite tailings surface, provides improved water/nutrient holding capacity, provides organic source for developing soil.	Rolled out over plots and secured with staples

Table 3.6. Mean species growth performance in the first field season.

Species	Cover (%)	Height (cm)
Arctagrostis latifolia (polar grass)	0.2 (0.0)	1.0 (0.0)
Calamagrostis canadensis (bluejoint)	0.5 (0.0)	1.0 (0.0)
Poa glauca (tundra bluegrass)	0.2 (0.0)	1.0 (0.1)
Poa alpina (alpine bluegrass)	0.7 (0.1)	2.0 (0.1)
Deschampsia beringensis (bering hairgrass)	1.1 (0.0)	3.5 (0.2)
Festuca rubra (creeping red fescue)	1.5 (0.1)	4.6 (0.5)
Deschampsia caespitosa (tufted hairgrass)	1.1 (0.1)	2.3 (0.1)

Table 3.7. Mean species growth performance in the second field season on amendment combinations that included peat moss.

Species	Cover (%)	Height (cm)	Shoot Biomass ($g\ m^{-2}$)
Arctagrostis latifolia (polar grass)	0 (0)	0 (0)	0 (0)
Calamagrostis canadensis (bluejoint)	5 (2)	24 (5)	5.9 (2)
Poa glauca (tundra bluegrass)	2 (1)	5 (2)	1.2 (1)
Poa alpina (alpine bluegrass)	11 (2)	7 (1)	63.1 (11)
Deschampsia beringensis (bering hairgrass)	53 (18)	44 (4)	213.6 (59)
Festuca rubra (creeping red fescue)	33 (11)	13 (2)	168.3 (25)
Deschampsia caespitosa (tufted hairgrass)	16 (5)	13 (5)	84.4 (20)

Table 3.8. Mean species growth performance in the second field season on amendment combinations that did not include peat moss.

Species	Cover (%)	Height (cm)	Shoot Biomass ($g\ m^{-2}$)
Arctagrostis latifolia (polar grass)	0 (0)	0 (0)	0 (0)
Calamagrostis canadensis (bluejoint)	4 (1)	18 (4)	3.2 (0)
Poa glauca (tundra bluegrass)	0 (0)	0 (0)	0 (0)
Poa alpina (alpine bluegrass)	3 (2)	7 (1)	12.3 (2)
Deschampsia beringensis (bering hairgrass)	18 (8)	6 (2)	87.8 (26)
Festuca rubra (creeping red fescue)	26 (9)	9 (4)	117.6 (22)
Deschampsia caespitosa (tufted hairgrass)	8 (4)	16 (6)	25.6 (13)

Table 3.9. Carbon, nitrogen and phosphorus totals for individual amendments based on field amendment application rates.

Amendment	Rate (kg ha^{-1})	Organic N (kg ha^{-1})	Mineral N (kg ha^{-1})	Total P (kg ha^{-1})	Total C (kg ha^{-1})	C:N ratio
Peat Moss	49040	515	5	13	16674	32:1
Lake Sediment	1029400	95	8	463	2059	20:1
Papermill Sludge	53740	606	34	137	21496	34:1
Agri-Boost	131120	3394	211	278	55070	15:1
Sewage Sludge	1075000	557	210	120	16125	21:1
Fertilizer	280	0	28	95	0	
Ammonium NO_3	75	0	25	0	0	

Dry biomass production = 3362 kg ha^{-1} (peat moss + sewage sludge + fertilizer + NH_4NO_3)
Shoot biomass total nitrogen is 1.13% = 38 kg ha^{-1}
Shoot biomass total phosphorus is 1200 mg kg^{-1} = 4 kg ha^{-1}

CHAPTER IV: RECOMMENDATIONS FOR LARGE SCALE KIMBERLITE TAILINGS RECLAMATION

4.1 RECOMMENDATIONS FOR FUTURE RESEARCH

The following actions for the Ekati™ Diamond Mine tailings reclamation project are recommended.

1. Continue monitoring plant growth and tailings properties, as annual environmental differences will affect the long-term sustainability of existing vegetation. Sustainability will also depend on the establishment of new plants from seed or vegetative growth produced by the seeded species used in reclamation or plants from the surrounding tundra. Amended tailings properties will change with time and subsequently plant growth will be affected (Sopher and Baird 1982). Monitoring the C:N ratio and the possibility of nutrient cycling on the amended tailings will be important in maintaining the established vegetation and assessing the sustainability and health of the reclaimed system.

2. Further explore the use of lake sediment as a structure improving amendment. This study suggests that lower application rates (<5 cm) under field conditions may prove beneficial to initial plant establishment and root biomass. In the first field season the two plots amended with 5 cm of lake sediment produced some of the highest ground cover at 33 and 38% (Table 3.1). Lake sediment is high in fine particles (69% silt and clay) and at reduced application rates should alter the texture of the Ekati kimberlite tailings. Increasing the fraction of fines in a coarse textured soil can improve water and nutrient holding capacities and provide a more favourable environment for microbial activity necessary for nutrient cycling (Hausenbuiller 1985). In the greenhouse study cation exchange capacity (CEC) was decreased with lake sediment additions (section 2.4.4.2). This reduction is likely a consequence of low organic C in the lake sediment (Table 2.2) as CEC is not simply a function of particle size but rather a function of charge and a substrate's molar absorption

potential (number of absorption sites) (Brady and Weil 1996). With silicate clays low in humic material, low molar ionic absorption potential can be expected and therefore low CEC (Brady and Weil 1996). Thus lake sediment should be further tested at reduced rates (<5 cm) in combination with an organic carbon source.

3. Continue testing amendment application rates under field conditions concentrating on reduced amounts of organic amendments. Both the greenhouse and field studies suggest that application rates of structure improving amendments were too high. Consideration of the C:N ratio of materials added to the tailings supports these finding and further suggests that reduced rates of organic matter can provide favourable plant growth conditions and more effectively facilitate the establishment of a nutrient cycle (Section 4.1).

4. Establish larger field study plots considering alternative amendments such as papermill sludge, compost and manure. The use of waste materials in reclamation is an effective means of increasing overall resource utilization and should be considered whenever possible (Section 1.6). The performance of sewage sludge and papermill sludge in the greenhouse study (Chapter 2) shows that waste materials can be employed as soil conditioners with equal or greater performance potential compared with traditional materials like peat moss (Belsito and Winterhalder 1999). Further testing of waste materials on the Ekati kimberlite tailings will not only aid in improving the substrate as a plant growth medium, but will reduce overall mine reclamation costs. In testing organic waste materials such as manures it is important to consider the C:N balance for long-term vegetation success (Chapter 3).

5. Consider using large boulder sized pieces of overburden waste rock in combination with tailings amendments to simulate the surrounding boulder fields of the undisturbed tundra. Undisturbed land surrounding the Ekati kimberlite tailings area is littered with boulders. These surface stones act as windbreaks creating numerous micro sites conducive to seed catch and moisture retention. The addition of large pieces of waste rock after tailings amendment would also create a more natural

looking landscape blending the tailings containment facility into the surrounding tundra.

6. Explore additional native species for use in reclamation considering the possibility of seed collection in the area. The performance of native species is much easier to predict than non-natives and native colonizers are more likely to facilitate natural succession on disturbed lands (Cargill and Chapin 1987). Seed collections from native populations in the area further increase the benefit of natives, as local populations are adapted to site-specific conditions and better represent the natural vegetation of the area.

4.2 References

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APPENDIX A – AMENDMENT ABBREVIATIONS AND SITE MAPS

Table 1. Abbreviations of amendment materials.

Amendment	Abbreviation
Peat Moss	P
Sewage Sludge	S
Lake Sediment	L
Papermill Sludge	PM
Agri-Boost	A
Fertilizer + Ammonium Nitrate	F
Calcium Carbonate	C
Gypsum	G
Rock Phosphate	R
Control (unamended kimberlite)	K

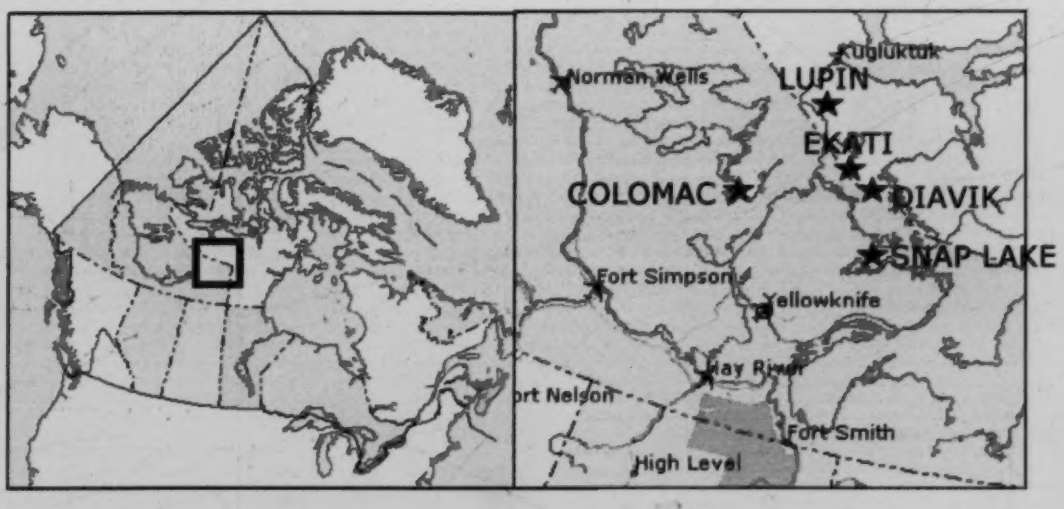

Figure 1. Diamond mining operations in the Northwest Territories.

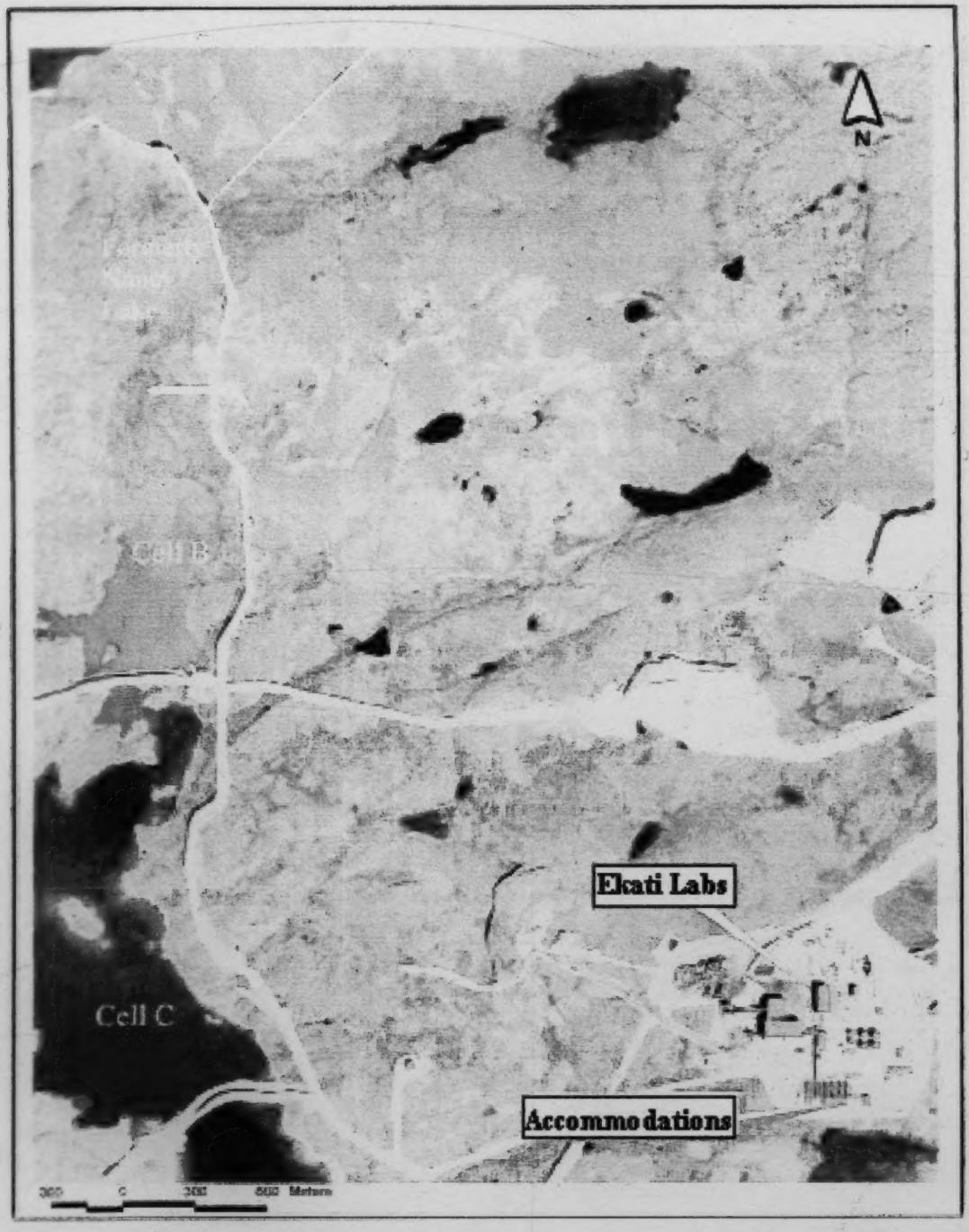

Figure 2. Site map of Ekati camp and Long Lake Containment Facility, Cell B.

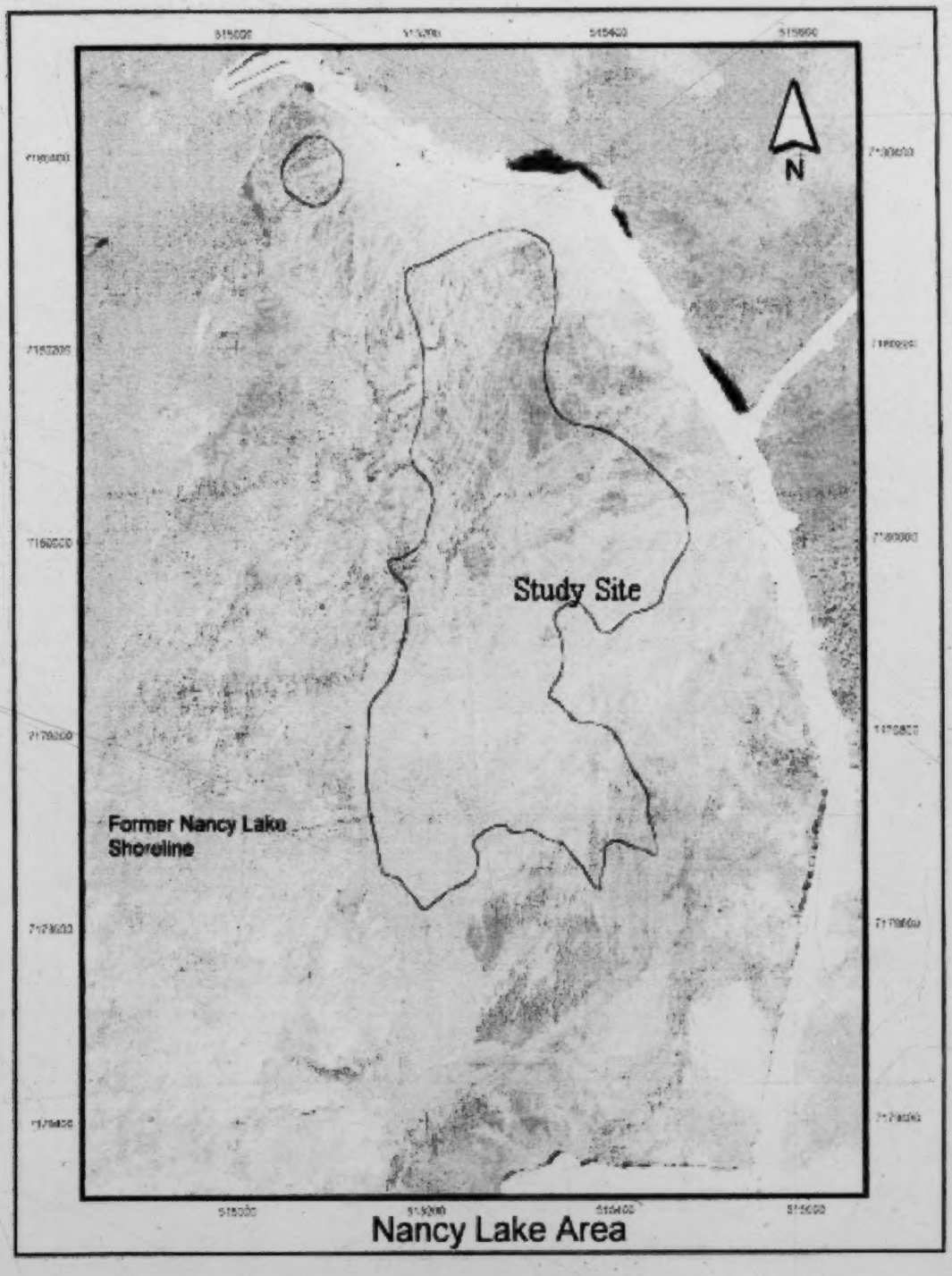

Figure 3. Cell B tailings containment area, north half. The study site is indicated on the eastern side of the solidified tailings area, near the access road.

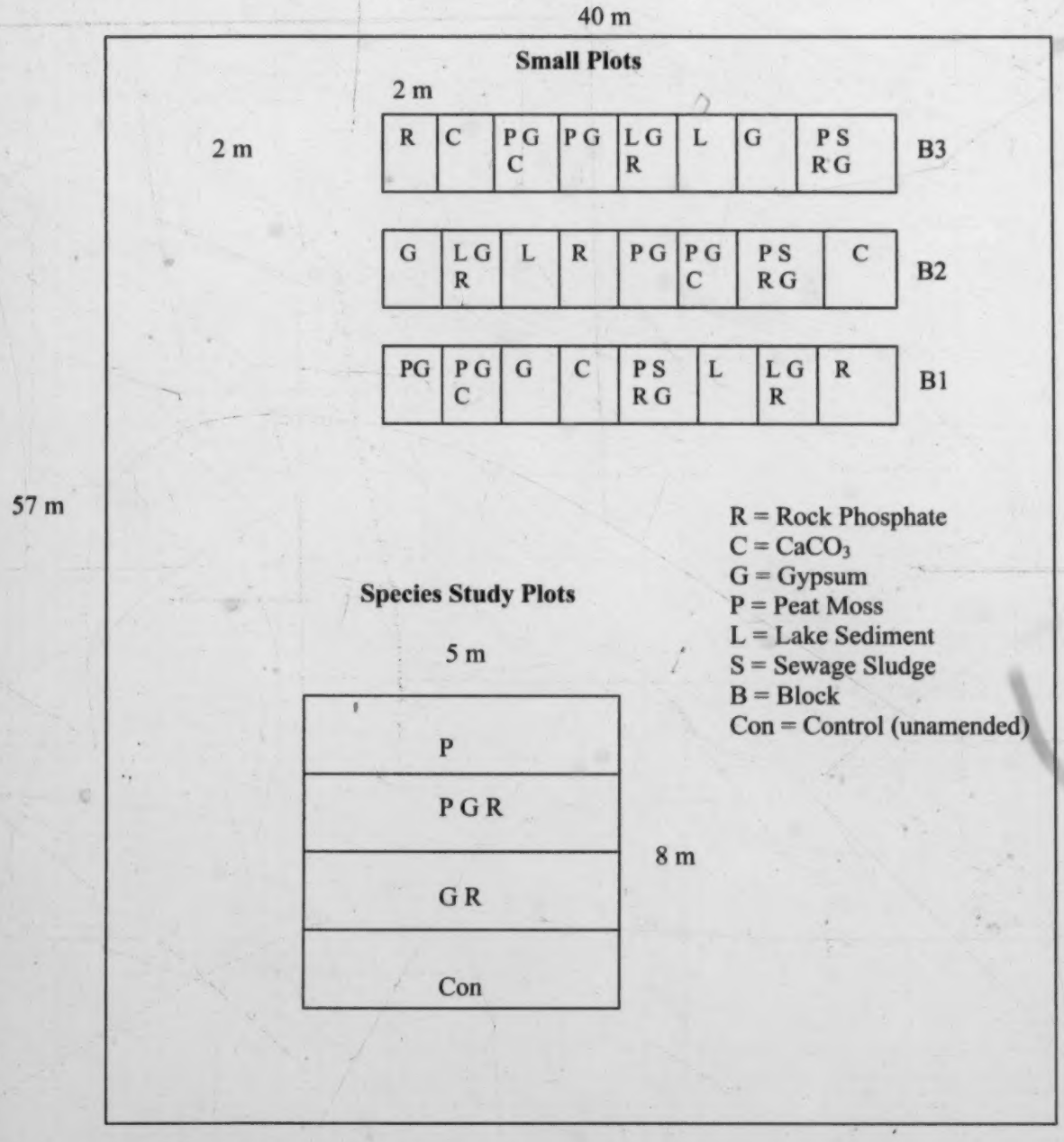

Figure 4. Plot set-up on Ekati processed kimberlite tailings Long Lake Containment Facility, Cell B.

APPENDIX B – STUDY SITE INFORMATION AND AMENDMENT PROPERTIES

Table 1. Mean monthly temperature and rainfall at Ekati Diamond Mine™ averaged for each month from November 1996 to June 2000.

Month (1996-2000)	Mean Temperature (°C)	Monthly Precipitation (mm)
January	-23.1	0.3
February	-26.9	0.0
March	-24.9	0.0
April	-19.4	0.7
May	-11.7	3.3
June	-2.2	6.7
July	8.6	47.2
August	12.8	14.0
September	10.7	65.0
October	2.8	21.6
November	-6.8	4.8
December	-18.9	0.1
Annual	-8.3	14.2

Table 3. Percent moisture of Ekati processed kimberlite tailings collected from Long Lake Containment Facility, Cell B.

Trial	Dry Soil (g)	Saturated Soil after 48 hr (g)	Weight Difference (g)	% Moisture
1	30.1	38.9	8.8	29.2
2	28.3	37.4	9.1	32.2
3	30.3	36.5	6.2	20.5
4	33.7	41.9	8.2	24.3

Mean soil moisture = 26.6%
Average weight of 12.5 cm pot filled with kimberlite = 950 g
Pot weight 950 g x percent moisture 0.266 = 252.7 g

APPENDIX C - RECLAMATION SPECIES

Table 1. The weight ratio of seed for each species in a 2.5 kg seed mix.

Species	Common Name	Weight ratio (2.25 kg mix)
Arctagrostis latifolia (R. Br.)	polar grass	0.53
Calamagrostis canadensis (Michx.)	bluejoint	0.17
Poa glauca (Vahl)	tundra bluegrass	0.27
Poa alpina (L.)	alpine bluegrass	0.40
Deschampsia beringensis (Hulten)	bering hairgrass	0.27
Festuca rubra (L.)	creeping red fescue	0.34
Deschampsia caespitosa (L.)	tufted hairgrass	0.27

Figure 1. Vegetation growth on peat moss + sewage sludge + gypsum + rock phosphate in the second field season (August 2001).

SPECIES PROFILES

Arctagrostis latifolia

Arctagrostis latifolia (polar grass) is a cultivar developed from indigenous Alaskan collections from a number of locations in the interior and western Alaska. Polar grass was developed for use in revegetation in and around Alaska (Klebesadel 1969). Polar grass is a northern latitude species with a broad circumpolar distribution. It occurs across Alaska, the Yukon and the Northwest Territories in a wide variety of plant communities and often in disturbed areas (Mitchell 1980a). Polar grass is a medium to tall grass not uncommonly growing to a height of 1.4 m, with relatively wide lax leaves and stout rhizomes that give it a conservative spreading habit. In open stands it forms dense robust clumps of leafy stems (Mitchell 1980a). Polar grass is recommended for use in revegetation mixes in arctic, alpine or costal tundra systems where recovery by native species is desired. Polar grass should be used in seed mixes that also include species better adapted to dry sites. Indicated seed production for *Arctagrostis latifolia* under field conditions is approximately 125 to 200 kg/ha, although higher yields can be obtained.

Calamagrostis canadensis

Calamagrostis canadensis (bluejoint) is a cultivar developed from indigenous Alaskan collections made throughout interior, western and south-central Alaska (Mitchell 1980b). Bluejoint is tolerant of severe cold and wind under tundra conditions and has strong resistance to snow mold infestations. Bluejoint is a tall grass with individuals reaching 1.8 m in height in dense clumps of leafy stems produced from medium sized rhizomes (Mitchell 1980b). Bluejoint usually grows much shorter on disturbed sites forming dense stands. The rhizomatous nature of this species does well to stabilize surface soils producing good ground cover even when nutrient availability is low.

Poa glauca

Poa glauca (tundra bluegrass) is a cultivar developed from indigenous Alaskan collections made along the Sagavanirktok River in arctic Alaska (Mitchell 1980c). Tundra bluegrass is a short to medium height tufted bluegrass commonly growing to a

height of 0.5 m. It produces a basal clump of narrow leaves and numerous flowers. The inflorescence is short and narrowly pyramidal. Tundra bluegrass is well adapted to dry soils occurring commonly along rivers and on slopes and bluffs. Tundra bluegrass has been used since 1972 as a revegetation species on the arctic oil fields at Prudhoe Bay and has been a reliable performer producing 300 to 1000 kg/ha of seed in second year growths. This species is recommended as a significant component of revegetation mixes for disturbed Arctic sites (Mitchell 1980c).

Poa alpina

Poa alpina (alpine bluegrass) is a cultivar developed in Alaska from collections originally made at high elevation sites near LaCure, Switzerland (Wright 1991). Alpine bluegrass is a low growing perennial bunchgrass native to Alaska, the Yukon, the Northwest Territories and other Arctic and boreal regions. One of the outstanding attributes of alpine bluegrass is its early seed maturation occurring in late June or early July with yields of 224 kg/ha clean seed (Wright 1991). The most attractive characteristic of alpine bluegrass in this tailings reclamation study is its erosion control capabilities. *Poa alpina* was developed specifically for erosion control on disturbed sites in the arctic, subarctic and boreal regions. Forming low growing rhizomatous mats alpine bluegrass works well to stabilize coarse texture substrate (Wright 1991).

Deschampsia beringensis* and *Deschampsia caespitosa

Tufted hairgrass is a cultivar based on indigenous plant collections made in Alaska and Iceland and bering hairgrass is a cultivar from collections made at Galeba on the Yukon River, the Talkeetna mountains of north Palmer and Iceland (Mitchell 1986). Both bering hairgrass and tufted hairgrass are bunch grasses with most of their leaves producing a large basal clump with numerous flowers characterized by long diffused inflorescences (Mitchell 1986). Tufted hairgrass tends to have shorter narrower leaves that are darker green than the taller, broader leaves of bering hairgrass. Seed production in both species under field conditions can be as high as 225 kg/ha however, 150 kg/ha is more commonly observed. In Alaska tufted hairgrass is mostly an inland grass while bering hairgrass is restricted to the costal areas and islands of the western to south-eastern

portions. Both of these species were selected for this project based on their native origins as well as their reputation for tolerance to low-fertility regimes and associated ability to survive on highly disturbed sites at northern latitudes (Mitchell 1986). These hairgrass species are known for their sustainability on disturbed sites and are commonly referred to as good low maintenance ground cover species.

Festucå rubra

Festuca rubra was selected based on previous greenhouse growth experiments testing Ekati's Koala Lake sediment as a growth medium (Kidd 1999). Creeping red fescue was selected by Kidd 1999 based on the species adaption to conditions at the Ekati mine site, its value as a wetland habitat species and its hardy reputation when used in revegetation of disturbed sites. Creeping red fescue is another Alaskan cultivar derived from numerous collections throughout the interior of Alaska. It is a common wetland Arctic species found throughout the circumpolar Arctic region (Kidd 1999). At more southern latitudes this species can present an invasive threat, however, at its natural latitude is a common and important component of many riparian plant systems.

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APPENDIX D – GREENHOUSE AMENDMENTS

GREENHOUSE AMENDMENT CALCULATIONS (amendments applied by volume)

Volume of standard greenhouse pot

Pot diameter = 12.5 cm
Pot height = 15 cm

Area of a circle = $\pi R^2 = 3.14159 \times 6.25^2 = 122.72\ cm^2$

Pot volume = area of base x height = $122.72 \times 15 = 1840.8\ cm^3$

Low peat application in the field = 4 cm diluted with 25 cm of tailings per unit area

Therefore 15 cm (pot depth) would need: 4 : 25 as X : 15

$25X = 4x15$ $X = 60/25 = 2.4$

2.4 cm added to each pot per unit area and each pot is 122.72 cm^2 in area therefore

$2.4 \times 122.72 = 294.53\ cm^3$ of peat was added to each pot

GREENHOUSE AMENDMENT CALCULATIONS (amendments applied by weight)

Gypsum application in the field was 2173 kg ha^{-1}

1 ha = 10000 m^2 and 1 m^2 = 10000 cm^2

Therefore 2173 kg : 10000 m^2 as X kg : 0.012272 m^2 (area of greenhouse pot)

$10000X = 2173 \times 0.012272$ $X = 26.667/10000 = 0.003$ kg of Gypsum/greenhouse pot

Table 1. Amendment combinations tested in greenhouse.

Session 1		Session 2		Session 3	
K (control)	GR	K (control)	P6GRF	K (control)	CLLS
CF	RF	P 2	P8GR	GL	CFP
GF	P	P 4	P8F	GH	CFLS
PGCF	S	P 6	P8GRF	RL	CHP
LGRF	PS	P 8	L5GR	RH	CHLS
LF	PSF	L 5	L5F	CL	FALP
PSRGF	PL	L 10	L5GRF	CH	FALLS
PGRF	PLGR	L 15	L10GR	FAL	FAFLS
GRF	PLGRF	S 5	L10F	FAH	FAHP
F	LS	S 10	L10GRF	GRL	FAHLS
R	LSGR	S 15	L15GR	GRH	GRLP
C	LSGRF	GR	L15F	CGL	GRLLS
G	LC	F	L15GRF	CGH	GRHP
PGC	LP	GRF	S5GR	GLP	GRHLS
L	LGR	P2GR	S5F	GLLS	CGLP
PSRG	SC	P2F	S5GRF	GFP	CGLLS
PGR	SGR	P2GRF	S10GR	GFLS	CGFLS
		P4GR	S10F	GHP	AG2
		P4F	S10GRF	GHLS	AG4
		P4GRF	S15GR	RLP	AG2GR
		P6GR	S15F	RLLS	AG4GR
		P6F	S15GRF	RFP	PS2
				RFLS	PS4
				RHP	PS2GR
				RHLS	PS4GR
				CLP	

Session 1: 34 Treatments x 4 Replicates = 136 pots (136 soil samples)
Session 2: 44 Treatments x 4 Replicates = 176 pots (176 soil samples)
Session 3: 51 Treatments x 4 Replicates = 204 pots (204 soil samples)
Following C, G and R – L = low and H = high
Amendment abbreviations (Appendix A, Table 1)

APPENDIX E – DUNCAN MULTIPLE RANGE ANALYSES

Amendment abbreviations (Appendix A, Table 1).

Greenhouse Session 1: Mean Height (cm)

Duncan Grouping			Mean	N	treat
	A		27.750	4	LSGR
	B		24.125	4	SGR
C	B		21.375	4	LS
C	B		21.250	4	PSRG
C	B		21.000	4	SCA
C	B		20.925	4	RF
C	D		19.750	4	LSGRF
C	D		19.750	4	PGCaF
C	D	E	19.125	4	GRF
C	D	E	19.100	4	PSRGF
C	D	E	18.875	4	PGRF
C	D	E	18.750	4	LGRF
C	D	E	18.500	4	S
C	D	E	18.250	4	GF
C	D	E	18.175	4	LF
C	D	E	18.000	4	LP
C	D	E	17.750	4	LCA
F	D	E	16.875	4	PS
F	D	E	16.475	4	PGCa
F	D	E	16.375	4	PSF
F	D	E	16.000	4	CaF
F		E	15.775	4	LPGR
F		E	15.750	4	F
F	G		14.125	4	Ca
F	G		13.625	4	L
F	G		13.500	4	PGR
F	G		13.375	4	LPGRF
	G		12.000	4	LGR
	G		11.875	4	R
	G		11.750	4	KIM
	G		11.600	4	G
	G		11.550	4	P
	G		11.000	4	GR

Greenhouse Session 1: Ground Cover (%)

Duncan Grouping						Mean	N	treat
			A			62.500	4	PGRF
	B		A			61.250	4	PGCaF
	B		A	C		60.000	4	PSRG
	B	D	A	C		56.250	4	PSF
	B	D	A	C		56.250	4	PSRGF
E	B	D	A	C		53.750	4	LSGR
E	B	D	A	C	F	52.500	4	PS
E	B	D	G	C	F	51.250	4	SGR
E	B	D	G	C	F	51.250	4	SCA
E		D	G	C	F	50.000	4	PGCa
E	H	D	G		F	46.250	4	GF
E	H	D	G		F	46.250	4	RF
E	H		G	I	F	45.000	4	LGRF
E	H		G	I	F	45.000	4	P
E	H	J	G	I	F	43.250	4	LF
	H	J	G	I	F	42.500	4	GRF
K	H	J	G	I		41.250	4	LP
K	H	J	L	I		38.750	4	LS
K	H	J	L	I		38.250	4	CaF
K	H	J	L	I	M	35.750	4	LSGRF
K		J	L	I	M	35.000	4	LPGR
K	N	J	L		M	33.000	4	LGR
K	N		L	O	M	30.750	4	LPGRF
	N		L	O	M	30.000	4	LCA
	N		P	O	M	27.500	4	F
	N		P	O	M	27.000	4	S
	N	Q	P	O		24.000	4	L
		Q	P	O		22.000	4	Ca
	R	Q	P	O		20.750	4	PGR
	R	Q	P			17.500	4	KIM
	R	Q				15.250	4	GR
	R	Q				14.500	4	G
	R					11.000	4	R

Greenhouse Session 1: Dry Shoot Biomass (g)

Duncan Grouping						Mean	N	treat
			A			1.7233	4	PGCaF
	B		A			1.6583	4	PSRGF
	B		A	C		1.5855	4	LSGRF
	B		A	C		1.5805	4	PSRG
	B		A	C		1.5783	4	SGR
	B	D	A	C		1.5368	4	SCA
	B	D	A	C		1.4805	4	PSF
	B	D	A	C		1.4250	4	LS
	B	D	A	C		1.4065	4	PGRF
E	B	D	A	C		1.3755	4	LSGR
E	B	D	F	C		1.2705	4	RF
E	G	D	F	C		1.1843	4	LF
E	G	D	F	H		1.1348	4	PS
E	G	D	F	H		1.1140	4	LGRF
E	G	I	F	H		0.9545	4	GRF
J	G	I	F	H		0.9365	4	GF
J	G	I	F	H	K	0.8680	4	F
J	G	I	F	H	K	0.8550	4	LP
J	G	I		H	K	0.8303	4	PGCa
J	G	I		H	K	0.8168	4	S
J	G	I	L	H	K	0.7940	4	CaF
J		I	L	H	K	0.7278	4	LCA
J		I	L	H	K	0.7115	4	LPGR
J		I	L	H	K	0.7105	4	LPGRF
J	M	I	L		K	0.6555	4	LGR
J	M	I	L		K	0.6213	4	P
J	M	I	L		K	0.5305	4	Ca
J	M		L		K	0.4900	4	PGR
	M		L		K	0.4478	4	L
	M		L			0.3523	4	G
	M					0.2623	4	KIM
	M					0.2560	4	GR
	M					0.2338	4	R

Greenhouse Session 2: Dry Root Biomass (g)

Duncan Grouping									Mean	N	treat
					A				2.4508	4	LS
					B				1.5948	4	PSRG
	C				B				1.3325	4	PGCaF
	C				B				1.3118	4	SGR
	C				B		D		1.2503	4	LGR
	C		E		B		D		1.2395	4	PSRGF
F	C		E		B		D		1.2313	4	PGRF
F	C		E		B		D		1.2210	4	PS
F	C		E		B		D		1.2095	4	PGCa
F	C		E		B		D	G	1.1318	4	LP
F	C		E		B		D	G	1.1230	4	LPGR
F	C		E		B		D	G	1.1225	4	LPGRF
F	C		E		B	H	D	G	1.0738	4	LGRF
F	C		E		B	H	D	G	1.0288	4	LSGR
F	C		E		B	H	D	G	1.0075	4	LF
F	C		E	I	B	H	D	G	0.9725	4	SCA
F	C		E	I	J	H	D	G	0.9310	4	PSF
F	C	K	E	I	J	H	D	G	0.8493	4	LSGRF
F	C	K	E	I	J	H	D	G	0.8140	4	CaF
F	C	K	E	I	J	H	D	G	0.8025	4	L
F	C	K	E	I	J	H	D	G	0.7973	4	LCA
F	C	K	E	I	J	H	D	G	0.7685	4	GF
F	C	K	E	I	J	H	D	G	0.7623	4	P
F	C	K	E	I	J	H	D	G	0.7003	4	PGR
F		K	E	I	J	H	D	G	0.6473	4	RF
F		K	E	I	J	H		G	0.5908	4	GRF
F		K		I	J	H		G	0.5798	4	Ca
		K		I	J	H		G	0.5183	4	S
		K		I	J	H			0.4703	4	F
		K		I	J				0.3475	4	G
		K			J				0.3035	4	GR
		K							0.2760	4	KIM
		K							0.2645	4	R

Greenhouse Session 2: Mean Height (cm)

Duncan Grouping									Mean	N	treat
					A				22.250	4	L15F
					A				22.125	4	S5F
	B				A				19.750	4	S15F
	B				A				19.625	4	S5GR
	B				A				19.375	4	L10F
	B				A				19.125	4	S15GRF
	B				C				18.000	4	S15
	B				C		D		17.750	4	P4F
	B		E		C		D		17.250	4	S10
F	B		E		C		D		16.750	4	S10GR
F	B		E		C		D	G	16.500	4	S15GR
F	B		E		C	H	D	G	16.250	4	P8GRF
F	B		E		C	H	D	G	16.000	4	GRF
F	B		E		C	H	D	G	16.000	4	P4GRF
F	B		E		C	H	D	G	16.000	4	P2F
F	B		E		C	H	D	G	15.750	4	L10GRF
F	B		E		C	H	D	G	15.625	4	S5
F	I		E		C	H	D	G	14.750	4	L15GRF
F	I		E	J	C	H	D	G	14.125	4	L5GRF
F	I	K	E	J	C	H	D	G	14.000	4	S10GRF
F	I	K	E	J	L	H	D	G	13.750	4	P6GRF
F	I	K	E	J	L	H	D	G	13.750	4	S5GRF
F	I	K	E	J	L	H		G	13.250	4	P6F
F	I	K	E	J	L	H		G	13.250	4	P8F
F	I	K		J	L	H		G	13.000	4	L15GR
F	I	K		J	L	H		G	12.875	4	L10GR
F	I	K		J	L	H		G	12.875	4	L5F
F	I	K		J	L	H		G	12.625	4	S10F
	I	K		J	L	H	M	G	12.375	4	P2GRF
	I	K		J	L	H	M		12.125	4	P6GR
	I	K	N	J	L		M		11.375	4	L5GR
	I	K	N	J	L		M		11.125	4	P4
O	I	K	N	J	L		M		10.750	4	GR
O		K	N	J	L		M		10.500	4	P4GR
O		K	N	J	L		M		10.250	4	P2GR
O		K	N	J	L		M		10.000	4	P6
O		K	N	J	L		M		9.875	4	F
O		K	N		L		M		9.750	4	P8GR
O			N		L		M		9.625	4	P8
O			N		L		M		9.500	4	P2
O			N				M		8.375	4	L5
O			N						7.750	4	K
O			N						7.500	4	L10
O									6.750	4	L15

Greenhouse Session 2: Ground Cover (%)

Duncan Grouping						Mean	N	treat
			A			70.750	4	S15F
			A			70.000	4	S15
	B		A			66.750	4	P4F
	B		A	C		62.750	4	L15GRF
	B	D	A	C		61.500	4	P4GRF
E	B	D	A	C		58.750	4	P8F
E	B	D	A	C		58.250	4	S5F
E	B	D	F	C		54.250	4	L10F
E	B	D	F	C		53.750	4	P8
E	B	D	F	C		53.500	4	P6F
E	B	D	F	C		53.250	4	P2F
E		D	F	C		52.000	4	P8GRF
E		D	F	C		52.000	4	L10GRF
E	G	D	F	C		49.500	4	P6
E	G	D	F			48.000	4	L15F
E	G	D	F			47.500	4	S10
E	G	D	F			47.500	4	S15GRF
E	G		F	H		45.250	4	S15GR
	G	I	F	H		43.750	4	P6GRF
J	G	I	F	H		41.500	4	P4
J	G	I	F	H		40.750	4	P4GR
J	G	I	F	H		40.750	4	P2
J	G	I	K	H		37.500	4	P8GR
J	G	I	K	H		37.000	4	GRF
J	G	I	K	H	L	35.250	4	P2GRF
J	M	I	K	H	L	33.000	4	S5GRF
J	M	I	K	H	L	32.000	4	S10GR
J	M	I	K	H	L	32.000	4	S10GRF
J	M	I	K		L	30.750	4	S5GR
J	M	I	K		L	30.750	4	L5
J	M	I	K		L	30.500	4	L5GR
J	M		K		L	28.000	4	S5
J	M		K		L	28.000	4	P6GR
J	M		K		L	27.750	4	L10GR
J	M		K	N	L	27.250	4	L10
	M	O	K	N	L	25.500	4	L5F
	M	O	K	N	L	24.500	4	L15
	M	O	K	N	L	23.750	4	GR
	M	O		N	L	22.000	4	K
	M	O		N	L	21.750	4	L15GR
	M	O		N		20.000	4	L5GRF
	M	O		N		19.750	4	S10F
		O		N		13.250	4	P2GR
		O				12.500	4	F

Greenhouse Session 2: Dry Shoot Biomass (g)

Duncan Grouping							Mean	N	treat
			A				3.9055	4	L10GRF
	B		A				2.7580	4	L5GR
	B		A		C		2.6427	4	L15F
	B		D		C		2.3678	4	S15F
	B	E	D		C		2.1817	4	L10F
	B	E	D		C		2.1670	4	S5F
	B	E	D		C		2.1190	4	S15GRF
F	B	E	D		C		2.0860	4	S10
F	B	E	D		C	G	1.9242	4	S15
F	B	E	D		C	G	1.9146	4	P4GRF
F	B	E	D	H	C	G	1.8706	4	P4F
F	B	E	D	H	C	G	1.6826	4	L15GRF
F	B	E	D	H	C	G	1.5394	4	P8F
F	B	E	D	H	C	G	1.4994	4	P8GRF
F	B	E	D	H	C	G	1.4253	4	S15GR
F	B	E	D	H	C	G	1.3558	4	P2F
F		E	D	H	C	G	1.2503	4	S10GR
F		E	D	H	C	G	1.2422	4	S10GRF
F		E	D	H		G	1.1650	4	GRF
F		E	D	H		G	1.1527	4	P6F
F		E	D	H		G	1.1344	4	P8GRF
F		E	D	H		G	1.1300	4	P4GR
F		E	D	H		G	1.1256	4	S5
F		E	D	H		G	1.0950	4	P8
F		E	D	H		G	1.0715	4	S5GR
F		E	D	H		G	1.0087	4	P6
F		E	D	H		G	1.0066	4	P2GRF
F		E	D	H		G	0.9620	4	S5GRF
F		E	D	H		G	0.9606	4	L10GR
F		E	D	H		G	0.9074	4	P2
F		E	D	H		G	0.8601	4	L5F
F		E		H		G	0.8159	4	L5GRF
F		E		H		G	0.7782	4	P6GR
F		E		H		G	0.7682	4	L15GR
F		E		H		G	0.7620	4	P4
F		E		H		G	0.7270	4	P8GR
F		E		H		G	0.7265	4	K
F		E		H		G	0.6680	4	S10F
F		E		H		G	0.6639	4	L5
F				H		G	0.5804	4	L10
				H		G	0.5195	4	F
				H		G	0.5093	4	L15
				H		G	0.4646	4	GR
				H			0.3635	4	P2GR

Greenhouse Session 2: Dry Root Biomass (g)

Duncan Grouping									Mean	N	treat
					A				4.1678	4	L10F
					A				3.8381	4	L15F
	B				A				3.5850	4	L10GR
	B				A		C		3.3914	4	L10GRF
	B				A		C		3.3848	4	S5F
	B		D		A		C		3.2564	4	L15GRF
E	B		D		A		C		3.0087	4	P8
E	B		D		A		C	F	2.9994	4	S15F
E	B		D		G		C	F	2.3765	4	L15GR
E	B		D		G		C	F	2.2685	4	P8GR
E	B		D		G	H	C	F	2.2288	4	P6F
E	B		D		G	H	C	F	2.1570	4	S10
E	B		D		G	H	C	F	2.1448	4	L5GR
E	B		D	I	G	H	C	F	2.1370	4	S15
E	B		D	I	G	H	C	F	2.1302	4	S5
E	J		D	I	G	H	C	F	2.0949	4	S10GR
E	J		D	I	G	H	C	F	2.0518	4	P4GRF
E	J	K	D	I	G	H	C	F	2.0013	4	P4F
E	J	K	D	I	G	H	C	F	1.9641	4	P6
E	J	K	D	I	G	H		F	1.8641	4	S5GR
E	J	K	D	I	G	H		F	1.8489	4	P6GR
E	J	K	D	I	G	H		F	1.7824	4	P8F
E	J	K		I	G	H		F	1.6441	4	L5
E	J	K		I	G	H		F	1.6210	4	P8GRF
E	J	K		I	G	H		F	1.5097	4	S15GRF
	J	K		I	G	H		F	1.5016	4	P4GR
	J	K		I	G	H			1.3564	4	S5GRF
	J	K		I	G	H			1.3034	4	S10GRF
	J	K		I	G	H			1.2940	4	K
	J	K		I	G	H			1.2906	4	L5F
	J	K		I	G	H			1.2586	4	P2F
	J	K		I	G	H			1.2562	4	L10
	J	K		I	G	H			1.2388	4	S15GR
	J	K		I	G	H			1.1922	4	P4
	J	K		I	G	H			1.0456	4	P2
	J	K		I	G	H			0.9644	4	GRF
	J	K		I	G	H			0.9389	4	P6GRF
	J	K		I	G	H			0.9095	4	P2GRF
	J	K		I		H			0.7155	4	S10F
	J	K		I		H			0.7093	4	L5GRF
	J	K		I		H			0.6941	4	L15
	J	K		I					0.6093	4	P2GR
	J	K							0.5918	4	GR
		K							0.4943	4	F

Greenhouse Session 3: Mean Height (cm)

Duncan Grouping							Mean	N	treat
			A				18.875	4	hFP
	B		A				17.375	4	lGLS
	B		A		C		16.625	4	PM4GR
	B	D	A		C		16.250	4	fGLS
	B	D	E		C		15.500	4	AG4GR
	B	D	E		C		15.375	4	fClGLS
	B	D	E		C		15.250	4	AG4
	B	D	E		C		15.250	4	fCfGLS
	B	D	E		C		15.250	4	PM2GR
	B	D	E		C		15.125	4	AG2GR
F	B	D	E		C		15.000	4	AG2
F	B	D	E		C		15.000	4	hGLS
F	B	D	E		C		14.875	4	PM4
F	G	D	E		C		14.000	4	lFP
F	G	D	E		C		13.750	4	hCLS
F	G	D	E		C		13.625	4	fGhRLS
F	G	D	E				13.250	4	fFLS
F	G	D	E		H		13.125	4	fGlRLS
F	G	D	E		H		13.000	4	PM2
F	G	D	E		H		13.000	4	hRLS
F	G	I	E		H		12.750	4	lRLS
F	G	I	E		H		12.625	4	fRLS
F	G	I	E		H	J	12.500	4	hFLS
F	G	I	E		H	J	12.500	4	fCLS
F	G	I	K		H	J	11.750	4	hCP
L	G	I	K		H	J	11.500	4	lCLS
L	G	I	K	M	H	J	10.750	4	lCP
L	N	I	K	M	H	J	10.000	4	hF
L	N	I	K	M	H	J	10.000	4	fClGP
L	N	I	K	M		J	9.750	4	hC
L	N	I	K	M		J	9.625	4	fRP
L	N		K	M	O	J	9.375	4	lRP
L	N	P	K	M	O		9.000	4	fCP
L	N	P	K	M	O		9.000	4	fGlRP
L	N	P	K	M	O		8.625	4	hRP
L	N	P	K	M	O		8.625	4	fChG
L	N	P	K	M	O		8.625	4	hGP
L	N	P	K	M	O		8.500	4	lF
L	N	P	K	M	O		8.500	4	fClG
L	N	P		M	O		8.375	4	fGRhP
L	N	P		M	O		8.250	4	lGP
L	N	P		M	O		8.250	4	fGP
	N	P		M	O		7.500	4	K
	N	P		M	O		7.500	4	lC
	N	P			O		7.375	4	lG
	N	P			O		7.250	4	fGhR
	N	P			O		7.250	4	fGlR
	N	P			O		7.000	4	lR
		P			O		6.250	4	hR
		P					5.750	4	hG

Greenhouse Session 3: Ground Cover (%)

Duncan Grouping									Mean	N	treat
					A				94.500	4	hFP
	B				A				85.250	4	PM4GR
	B				C				76.500	4	PM4
	B				C		D		75.750	4	PM2
					C		D		70.500	4	hCLS
	E				C		D		64.750	4	fCfGLS
	E				F		D		63.500	4	fClGLS
	E				F		G		57.500	4	lFP
	E		H		F		G		55.000	4	lCP
I	E		H		F		G		53.000	4	fFLS
I	J		H		F		G		51.000	4	lGLS
I	J		H		K		G		49.500	4	fRLS
I	J		H		K		G	L	49.000	4	hCP
I	J		H		K		G	L	48.000	4	hGLS
I	J		H		K		G	L	48.000	4	AG4GR
I	J		H		K		G	L	47.750	4	lRLS
I	J		H		K	M	G	L	47.250	4	fGlRLS
I	J		H	N	K	M	G	L	46.000	4	fCLS
I	J		H	N	K	M	G	L	45.500	4	fGLS
I	J		H	N	K	M	G	L	44.250	4	fClGP
I	J		H	N	K	M	O	L	43.500	4	hFLS
I	J	P	H	N	K	M	O	L	42.500	4	fGhRLS
I	J	P	Q	N	K	M	O	L	40.500	4	AG2GR
I	J	P	Q	N	K	M	O	L	40.500	4	lRP
I	J	P	Q	N	K	M	O	L	40.000	4	fCP
	J	P	Q	N	K	M	O	L	37.500	4	AG2
	J	P	Q	N	K	M	O	L	37.000	4	fGRhP
		P	Q	N	K	M	O	L	36.500	4	fGP
		P	Q	N	K	M	O	L	36.000	4	hRLS
		P	Q	N	K	M	O	L	35.500	4	PM2GR
		P	Q	N	K	M	O	L	35.500	4	fGlRP
		P	Q	N		M	O	L	35.000	4	hGP
		P	Q	N	R	M	O		33.250	4	lCLS
		P	Q	N	R		O		32.750	4	hRP
		P	Q		R		O		29.750	4	AG4
		P	Q		R				29.250	4	fRP
	S		Q		R				27.750	4	lGP
	S		Q		R		T		27.000	4	hF
	S		U		R		T		21.250	4	fGlR
	S		U		R		T		20.750	4	fClG
	S		U				T		15.500	4	lG
	S		U				T		15.000	4	lR
	S		U				T		15.000	4	hC
			U				T		14.250	4	fChG
			U						13.500	4	K
			U						12.500	4	fGhR
			U						11.000	4	lF
			U						10.500	4	lC
			U						9.500	4	hR
			U						8.750	4	hG

Greenhouse Session 3: Dry Shoot Biomass (g)

Duncan Grouping														Mean	N	treat
								A						3.0274	4	hFP
			B					A						2.6670	4	PM4GR
			B					C						2.2950	4	fClGLS
			D					C						2.0860	4	PM4
			D					C		E				2.0043	4	fCfGLS
			D		F			C		E				1.8170	4	hCLS
			D		F			G		E				1.6804	4	PM2
			D		F			G		E				1.6598	4	lGLS
			D		F			G		E				1.5808	4	fFLS
		H	D		F			G		E				1.5538	4	PM2GR
		H	I		F			G		E				1.4990	4	lRLS
		H	I		F			G		J				1.4268	4	lFP
		H	I		F			G		J				1.3925	4	hRLS
		H	I		F			G		J				1.3599	4	hGLS
		H	I		F			G		J		K		1.3275	4	hFLS
		H	I		F			G	L	J		K		1.2975	4	fCLS
		H	I		F		M	G	L	J		K		1.2775	4	AG4GR
		H	I		F		M	G	L	J		K		1.2698	4	fGLS
		H	I		N		M	G	L	J		K		1.1725	4	lCP
		H	I	O	N		M	G	L	J		K		1.1005	4	hCP
		H	P	I	O	N	M	G	L	J		K		1.0963	4	lF
	Q	H	P	I	O	N	M	G	L	J		K		1.0903	4	lRP
	Q	H	P	I	O	N	M	G	L	J		K		1.0898	4	fGhRLS
	Q	H	P	I	O	N	M	G	L	J		K	R	1.0703	4	fRLS
	Q	H	P	I	O	N	M	S	L	J		K	R	0.9595	4	lCLS
	Q	H	P	I	O	N	M	S	L	J		K	R	0.9563	4	fGlRLS
	Q	T	P	I	O	N	M	S	L	J		K	R	0.8930	4	AG2
	Q	T	P	U	O	N	M	S	L	J		K	R	0.8790	4	fCP
	Q	T	P	U	O	N	M	S	L	J		K	R	0.8588	4	AG2GR
	Q	T	P	U	O	N	M	S	L	J	V	K	R	0.8318	4	hRP
	Q	T	P	U	O	N	M	S	L	J	V	K	R	0.8208	4	hGP
	Q	T	P	U	O	N	M	S	L		V	K	R	0.7268	4	lGP
	Q	T	P	U	O	N	M	S	L		V		R	0.7120	4	fGP
	Q	T	P	U	O	N	M	S		W	V		R	0.6760	4	fGlR
	Q	T	P	U	O	N	M	S		W	V		R	0.6680	4	fRP
	Q	T	P	U	O	N		S		W	V		R	0.6225	4	fClGP
	Q	T	P	U	O	N		S		W	V		R	0.5895	4	fClG
	Q	T	P	U	O			S		W	V		R	0.5382	4	fGlRP
	Q	T	P	U	O			S		W	V		R	0.5363	4	fChG
	Q	T	P	U				S		W	V		R	0.4830	4	AG4
	Q	T		U				S		W	V		R	0.4780	4	fGhR
		T		U				S		W	V		R	0.4688	4	fGRhP
		T		U				S		W	V		R	0.4658	4	hC
		T		U				S		W	V			0.3535	4	hF
		T		U						W	V			0.3140	4	lG
				U						W	V			0.2733	4	hG
										W	V			0.2261	4	lR
										W	V			0.2255	4	K
										W	V			0.2228	4	lC
										W				0.0945	4	hR

Greenhouse Session 3: Dry Root Biomass (g)

Duncan Grouping								Mean	N	treat
				A				3.7201	4	hGLS
				A				3.6025	4	PM4GR
				A				3.1968	4	hRLS
	B			A				2.9700	4	fClGLS
	B			A				2.9658	4	lGLS
	B			A		C		2.7028	4	lRLS
	B			D		C		2.0660	4	PM2GR
	B			D		C		2.0348	4	fGLS
	B	E		D		C		2.0150	4	fCfGLS
F	B	E		D		C		1.9693	4	hRP
F	G	E		D		C		1.7468	4	lFP
F	G	E		D		C	H	1.6643	4	hCLS
F	G	E		D		C	H	1.6443	4	hFP
F	G	E		D		C	H	1.6393	4	PM4
F	G	E		D			H	1.6262	4	fGlRLS
F	G	E		D			H	1.5593	4	fCP
F	G	E		D			H	1.5393	4	PM2
F	G	E		D			H	1.5163	4	fClG
F	G	E		D			H	1.5053	4	hCP
F	G	E		D		I	H	1.4398	4	lRP
F	G	E		D	J	I	H	1.3515	4	lCP
F	G	E		D	J	I	H	1.3345	4	fGhRLS
F	G	E	K	D	J	I	H	1.1870	4	lCLS
F	G	E	K	D	J	I	H	1.1855	4	hGP
F	G	E	K	D	J	I	H	1.1828	4	fFLS
F	G	E	K	D	J	I	H	1.1772	4	fGlRP
F	G	E	K	D	J	I	H	1.0887	4	fRP
F	G	E	K	D	J	I	H	1.0368	4	fRLS
F	G	E	K	D	J	I	H	1.0118	4	fCLS
F	G	E	K	D	J	I	H	0.9715	4	lF
F	G	E	K		J	I	H	0.8878	4	lGP
F	G	E	K		J	I	H	0.8850	4	hFLS
F	G		K		J	I	H	0.8595	4	fClGP
F	G		K		J	I	H	0.8548	4	fGlR
	G		K		J	I	H	0.8028	4	fGP
	G		K		J	I	H	0.6750	4	AG4GR
	G		K		J	I	H	0.6213	4	fGRhP
			K		J	I	H	0.5898	4	hC
			K		J	I	H	0.5500	4	AG2
			K		J	I	H	0.5398	4	fGhR
			K		J	I	H	0.5205	4	fChG
			K		J	I		0.3406	4	AG2GR
			K		J	I		0.3350	4	lG
			K		J			0.2355	4	lC
			K		J			0.2300	4	AG4
			K		J			0.2236	4	lR
			K					0.1820	4	K
			K					0.1820	4	hG
			K					0.1405	4	hF
			K					0.1025	4	hR

Field Season 1: Mean Height (cm)

Duncan Grouping		Mean	N	treat
	A	3.8889	9	PSRG
	B	2.7778	9	LGR
C	B	1.9444	9	L
C		1.8333	9	PG
C		1.6667	9	PGCa
C	D	1.5000	9	R
	D	0.6667	9	G
	D	0.6111	9	Ca

Field Season 1: Ground Cover (%)

Duncan Grouping		Mean	N	treat
	A	37.778	9	LGR
	A	33.000	9	L
	A	31.667	9	PSRG
	B	16.889	9	PG
	B	16.444	9	PGCa
C	B	6.444	9	R
C		4.222	9	Ca
C		3. 778	9	G

Field Season 2: Mean Height (cm)

Duncan Grouping			Mean	N	treat
	A		42.556	9	PSRG
	B		24.889	9	LGR
C	B		22.667	9	L
C			17.889	9	PG
C			16.889	9	PGCa
	D		9.611	9	Ca
	D		8.333	9	R
	D		4.500	9	G

Field Season 2: Ground Cover (%)

Duncan Grouping			Mean	N	treat
	A		69.556	9	PSRG
	B		22.444	9	LGR
C	B		18.333	9	L
C	B	D	13.111	9	PGCa
C		D	8.111	9	PG
		D	4.333	9	Ca
		D	3.000	9	R
		D	1.556	9	G

Field Season 2: Dry Shoot Biomass (g)

Duncan Grouping		Mean	N	treat
	A	33.617	9	PSRG
	B	12.937	9	LGR
	B	11.277	9	L
C	B	8.430	9	PGCa
C	D	4.553	9	PG
	D	2.683	9	Ca
	D	1.620	9	R
	D	0.527	9	G

Greenhouse Session 1: Available N (mg kg^{-1})

Duncan Grouping			Mean	N	treat
	A		10.5000	4	PS
	A		10.0500	4	PSRGF
	B		4.5500	4	CaF
C	B		4.2000	4	LGRF
C	B	D	3.3500	4	LSGR
C	B	D	3.2000	4	PSF
C	B	D	2.9500	4	P
C		D	2.6500	4	Ca
C		D	2.5500	4	PGRF
C		D	2.5000	4	PGCa
C		D	2.4500	4	S
C		D	2.4000	4	F
C		D	2.4000	4	PGR
		D	2.3000	2	GRP
		D	2.2000	4	SCA
		D	2.2000	4	PSRG
		D	2.2000	2	GR
		D	2.1000	4	RF
		D	1.9500	4	SGR
		D	1.9500	4	LF
		D	1.9000	4	LP
		D	1.9000	4	G
		D	1.8500	4	L
		D	1.8500	4	GF
		D	1.8000	4	LPGR
		D	1.7500	4	GRF
		D	1.7500	4	KIM
		D	1.7500	4	PGCaF
		D	1.7000	4	LGR
		D	1.7000	4	R
		D	1.7000	4	LPGRF
		D	1.7000	4	LSGRF
		D	1.7000	4	LCA
		D	1.7000	4	LS

Green Session 1: Available P (mg kg^{-1})

Duncan Grouping					Mean	N	treat
			A		59.250	4	PSRGF
			A		57.500	4	PGCaF
	B		A		56.000	4	PGRF
	B		C		48.750	4	LGRF
	D		C		41.750	4	LF
	D				41.000	4	PSF
	D		E		38.000	4	RF
	D		E		37.250	4	CaF
	D		E		34.000	4	R
	D		E		34.000	4	F
			E		32.750	4	GRF
			F		24.750	4	SCA
	G		F		23.750	4	PS
	G		F	H	23.000	4	GF
	G	I	F	H	21.000	4	PSRG
J	G	I	F	H	18.500	4	LSGRF
J	G	I	F	H	18.250	4	SGR
J	G	I	F	H	16.500	4	S
J	G	I		H	16.000	4	LS
J		I		H	15.000	2	GRP
J		I		H	14.750	4	LSGR
J		I			14.250	4	Ca
J		I			13.500	4	PGR
J		I			13.500	2	GR
J		I			13.250	4	LCA
J		I			13.000	4	P
J		I			12.750	4	PGCa
J					11.750	4	L
J					11.250	4	LGR
J					11.250	4	LPGR
J					11.000	4	LP
J					11.000	4	G
J					10.500	4	KIM
J					10.500	4	LPGRF

Greenhouse Session 1: Available K (mg kg^{-1})

Duncan Grouping				Mean	N	treat
		A		236.50	4	PGR
B		A		220.00	2	GR
B		A	C	215.75	4	G
B		D	C	199.75	4	PSRGF
B		D	C	199.00	2	GRP
B	E	D	C	196.25	4	CaF
	E	D	C	192.50	4	RF
	E	D	C	192.00	4	KIM
F	E	D	C	190.00	4	PGRF
F	E	D	C	189.75	4	S
F	E	D	C	189.00	4	GF
F	E	D	G	186.50	4	SCA
F	E	D	G	186.00	4	Ca
F	E	D	G	185.75	4	PSF
H F	E	D	G	184.50	4	SGR
H F	E	D	G	184.00	4	PGCa
H F	E	D	G	183.25	4	GRF
H F	E	D	G	181.25	4	PGCaF
H F	E	D	G	179.00	4	R
H F	E	D	G	176.00	4	F
H F	E	D	G	174.25	4	P
H F	E		G	167.75	4	PS
H F		I	G	162.50	4	PSRG
H F		I	G	162.00	4	LCA
H J		I	G	159.00	4	L
H J		I	K	156.00	4	LF
J	L	I	K	136.75	4	LGR
J	L		K	133.25	4	LP
J	L		K	132.50	4	LPGRF
	L		K	129.75	4	LS
	L		K	129.50	4	LGRF
	L			125.00	4	LPGR
	L			120.00	4	LSGRF
	L			115.00	4	LSGR

Greenhouse Session 1: Available S (mg kg^{-1})

Duncan Grouping								Mean	N	treat
				A				1100.0	2	GR
	B			A				941.0	2	GRP
	B			C				805.5	4	SGR
	B			C		D		731.5	4	PSRGF
	E			C		D		692.0	4	PGCaF
	E	F		C		D		644.0	4	PSRG
G	E	F		C		D		636.5	4	LSGRF
G	E	F		H		D		565.5	4	G
G	E	F		H		D	I	539.0	4	S
G	E	F		H	J	D	I	511.0	4	PGCa
G	E	F		H	J	K	I	478.5	4	PGR
G	E	F		H	J	K	I	451.5	4	PGRF
G		F		H	J	K	I	443.5	4	GRF
G		F		H	J	K	I	441.0	4	SCA
G	L	F		H	J	K	I	428.5	4	GF
G	L	M		H	J	K	I	393.8	4	PSF
N	L	M		H	J	K	I	368.0	4	PS
N	L	M	O	H	J	K	I	338.3	4	LGRF
N	L	M	O	H	J	K	I	338.0	4	R
N	L	M	O	H	J	K	I	336.8	4	Ca
N	L	M	O	H	J	K	I	322.5	4	LPGR
N	L	M	O		J	K	I	310.0	4	P
N	L	M	O		J	K	I	297.5	4	LGR
N	L	M	O		J	K	I	294.0	4	LPGRF
N	L	M	O		J	K	I	285.0	4	KIM
N	L	M	O	P	J	K		275.8	4	LSGR
N	L	M	O	P	J	K		260.5	4	CaF
N	L	M	O	P		K		251.8	4	F
N	L	M	O	P				178.0	4	LS
N		M	O	P				167.5	4	L
N			O	P				133.0	4	RF
N			O	P				129.8	4	LCA
			O	P				88.0	4	LP
				P				36.3	4	LF

Greenhouse Session 1: CEC (meq 100 g^{-1})

Duncan Grouping				Mean	N	treat
		A		24.3500	4	PGCa
	B	A		24.0000	4	PGCaF
	B	A		23.9250	4	PGRF
	B	A		23.9250	4	PGR
	B	A		23.8750	4	P
	B	A	C	23.6500	4	PSRG
	B	A	C	23.6500	4	PSF
	B	A	C	23.2750	4	PS
	B	A	C	23.1500	4	PSRGF
	B D	A	C	22.6500	4	SGR
	B D	E	C	22.1500	4	SCA
	F D	E	C	22.0250	4	S
	F D	E	G	21.2250	4	KIM
H	F D	E	G	21.1000	2	GR
H	F	E	G	20.6500	2	GRP
H	F	E	G	20.5250	4	F
H	F	E	G	20.5000	4	GRF
H	F		G	20.2500	4	G
H	F		G	20.2500	4	RF
H			G	20.0500	4	R
H		I	G	19.5250	4	Ca
H		I	G	19.5250	4	CaF
H		I		19.3000	4	GF
H		I		19.2500	4	LPGRF
H		I		19.2250	4	LPGR
		I		18.1750	4	LP
		J		15.8000	4	LCA
	K	J		14.7500	4	LGRF
	K			13.8750	4	L
	K			13.6750	4	LSGRF
	K			13.5500	4	LS
	K			13.5250	4	LF
	K			13.4750	4	LGR
	K			13.4250	4	LSGR

Greenhouse Session 1: Total Carbon (%)

Duncan Grouping			Mean	N	treat
	A		1.7000	4	PSF
B	A		1.5750	4	PSRGF
B	A		1.5750	4	PGCaF
B	A		1.5500	4	PGCa
B	A		1.5250	4	PSRG
B	A	C	1.4500	4	PS
B		C	1.3500	4	PGRF
B		C	1.3250	4	LPGR
	D	C	1.2250	4	LPGRF
	D	C	1.2250	4	LP
	D	C	1.2000	4	PGR
	D		1.0250	4	P
	E		0.4500	4	F
F	E		0.4000	4	S
F	E		0.4000	4	SCA
F	E		0.4000	4	GRF
F	E		0.3750	4	SGR
F	E		0.3500	4	G
F	E		0.3500	4	Ca
F	E		0.3250	4	GF
F	E		0.3000	2	GR
F	E		0.2500	4	RF
F	E		0.2250	4	CaF
F	E		0.2250	4	KIM
F	E		0.2000	4	LGRF
F	E		0.2000	2	GRP
F	E		0.2000	4	L
F	E		0.2000	4	R
F	E		0.2000	4	LGR
F	E		0.2000	4	LS
F	E		0.1750	4	LCA
F	E		0.1750	4	LF
F	E		0.1500	4	LSGR
F			0.0875	4	LSGRF

Greenhouse Session 2: Available N (mg kg^{-1})

Duncan Grouping								Mean	N	treat
				A				92.50	4	S10F
				B				62.50	4	S5GRF
				B				61.50	4	F
	C			B				59.25	4	S10GRF
	C			B		D		55.50	4	S15GRF
	C	E		B		D		53.25	4	S15F
F	C	E		B		D		48.75	4	L5GRF
F	C	E		B		D	G	44.00	4	P6GRF
F	C	E		B		D	G	42.00	4	P8GRF
F	C	E		B	H	D	G	37.50	4	P2GRF
F	C	E	I	B	H	D	G	34.25	4	S15
F	C	E	I	J	H	D	G	31.50	4	L5F
F		E	I	J	H	D	G	29.75	4	P8F
F		E	I	J	H		G	25.00	4	S5F
F			I	J	H		G	23.00	4	S15GR
F			I	J	H		G	21.00	4	GRF
			I	J	H		G	18.00	4	P2F
			I	J	H			9.75	4	L15F
			I	J	H			9.50	4	S5
			I	J				7.75	4	S5GR
			I	J				6.50	4	S10GR
				J				4.00	4	P4F
				J				3.50	4	GR
				J				2.75	4	P8GR
				J				2.50	4	P2
				J				2.50	4	S10
				J				2.50	4	L10F
				J				2.25	4	P8
				J				2.00	4	P6
				J				2.00	4	L15
				J				2.00	4	K
				J				1.75	4	L10GR
				J				1.75	4	P4
				J				1.75	4	L5
				J				1.75	4	L10
				J				1.75	4	L10GRF
				J				1.75	4	P6F
				J				1.50	4	L5GR
				J				1.25	4	L15GRF
				J				1.00	4	P6GR
				J				1.00	4	P2GR
				J				1.00	4	P4GR
				J				1.00	4	P4GRF
				J				0.25	4	L15GR

Greenhouse Session 2: Available P (mg kg^{-1})

Duncan Grouping	Mean	N	treat
A	299.00	4	L10GRF
B	93.75	4	L10GR
B	80.00	4	S15GRF
B	71.75	4	S15F
B	67.00	4	S10F
B	54.25	4	L15F
B	53.75	4	F
B	53.25	4	GRF
B	51.25	4	S5F
B	49.50	4	L5GRF
B	49.25	4	S5
B	49.25	4	S10GRF
B	48.50	4	P8GRF
B	45.50	4	S15GR
B	44.00	4	S5GRF
B	41.00	4	P8F
B	38.25	4	P6GRF
B	36.75	4	P2GRF
B	34.75	4	L15GRF
B	34.25	4	S15
B	31.50	4	S10GR
B	30.50	4	S10
B	29.25	4	S5GR
B	27.00	4	GR
B	26.75	4	P2F
B	26.00	4	P4GRF
B	24.50	4	P8GR
B	23.50	4	P2
B	23.50	4	L10F
B	23.50	4	P6F
B	22.50	4	P2GR
B	22.25	4	L15
B	22.25	4	L5GR
B	21.25	4	L5F
B	21.00	4	P8
B	20.75	4	L15GR
B	20.00	4	P4F
B	18.50	4	P4
B	18.50	4	K
B	15.75	4	P6
B	15.25	4	L5
B	12.75	4	P6GR
B	9.00	4	P4GR
B	8.50	4	L10

Greenhouse Session 2: Available K (mg kg^{-1})

Duncan Grouping							Mean	N	treat
			A				227.50	4	S5GRF
	B		A				221.50	4	S10F
	B		A		C		207.25	4	F
	B		D		C		203.75	4	P2GRF
	B		D		C		202.00	4	P2GR
	B	E	D		C		199.25	4	S10GRF
	F	E	D		C		197.75	4	S5GR
G	F	E	D		C		196.00	4	S10GR
G	F	E	D		C		194.25	4	P2
G	F	E	D		C		194.25	4	S5F
G	F	E	D		C		193.75	4	GRF
G	F	E	D		C	H	192.75	4	S5
G	F	E	D		C	H	192.50	4	P4F
G	F	E	D		C	H	192.50	4	S15GRF
G	F	E	D		C	H	192.00	4	K
G	F	E	D		C	H	191.00	4	GR
G	F	E	D		C	H	189.00	4	S15F
G	F	E	D		C	H	188.75	4	P6
G	F	E	D		C	H	188.50	4	P4
G	F	E	D		C	H	187.75	4	P8F
G	F	E	D		C	H	187.50	4	S15GR
G	F	E	D		C	H	186.75	4	P6GRF
G	F	E	D		C	H	185.25	4	S10
G	F	E	D	I	C	H	184.00	4	P8
G	F	E	D	I	C	H	182.50	4	P4GR
G	F	E	D	I		H	179.25	4	P4GRF
G	F	E		I		H	175.25	4	P6GR
G	F			I		H	173.50	4	P8GRF
G	F			I		H	173.25	4	P2F
G	F			I		H	173.00	4	S15
G				I		H	171.00	4	P6F
				I		H	168.00	4	P8GR
			J	I			160.50	4	L5
	K		J				146.25	4	L5GRF
	K		L				132.50	4	L5F
	M		L				120.25	4	L5GR
	M		L				114.00	4	L10
	M		N				105.50	4	L10GRF
	M		N				105.50	4	L15
	M		N		O		100.75	4	L10F
	M		N		O		99.00	4	L10GR
			N		O		84.75	4	L15GRF
					O		79.75	4	L15GR
					O		78.75	4	L15F

Greenhouse Session 2: Available S (mg kg^{-1})

Duncan Grouping							Mean	N	treat
			A				1365.0	4	P6GRF
	B		A				1347.5	4	P8GR
	B		A		C		1250.5	4	P2GRF
	B		A		C		1225.0	4	P8GRF
	B	D	A		C		1145.0	4	GR
	B	D	E		C		1107.0	4	P6GR
	F	D	E		C		1022.0	4	S5GR
	F	D	E		C		1014.0	4	S5GRF
	F	D	E		G		919.5	4	P2F
	F	D	E		G		900.5	4	GRF
	F		E		G		879.0	4	P4GR
	F		E		G		875.0	4	P4F
	F		H		G		846.0	4	P4GRF
	F		H		G		843.5	4	S10GR
	F	I	H		G		788.0	4	P8F
J	F	I	H		G		779.5	4	P2GR
J	K	I	H		G		744.5	4	P6F
J	K	I	H		G		719.0	4	S10GRF
J	K	I	H		G	L	708.5	4	F
J	K	I	H	M	G	L	687.0	4	L5GRF
J	K	I	H	M	G	L	660.5	4	S15GR
J	K	I	H	M	N	L	611.5	4	L5GR
J	K	I	O	M	N	L	584.0	4	S5F
J	K	I	O	M	N	L	541.0	4	S15GRF
J	K	P	O	M	N	L	523.0	4	S10F
	K	P	O	M	N	L	508.0	4	S15F
	K	P	O	M	N	L	497.5	4	S5
	Q	P	O	M	N	L	450.3	4	S10
	Q	P	O	M	N		440.5	4	L10GRF
	Q	P	O	M	N		437.5	4	L10GR
R	Q	P	O		N		386.0	4	P8
R	Q	P	O		N		370.8	4	S15
R	Q	P	O		N		362.0	4	L5F
R	Q	P	O		N		361.8	4	P6
R	Q	P	O				322.0	4	L10F
R	Q	P					273.5	4	L15F
R	Q						227.3	4	L15GRF
R	Q						218.8	4	L15
R	Q						195.8	4	P4
R	Q						190.3	4	P2
R							162.3	4	L10
R							152.0	4	K
R							146.5	4	L15GR
R							123.3	4	L5

Greenhouse Session 1: CEC (meq 100 g^{-1})

Duncan Grouping					Mean	N	treat
			A		29.5000	4	P8
			B		26.5000	4	P6
			C		23.2500	4	P4
	D		C		22.7500	4	P4F
	D		E		21.5000	4	P4GRF
	D		E		21.5000	4	P4GR
			E		21.2500	4	P2
	F		E		21.0000	4	P2GR
	F		E	G	20.7500	4	F
	F	H	E	G	20.5000	4	P2F
	F	H	E	G	20.5000	4	P2GRF
I	F	H	E	G	20.3750	4	P8F
I	F	H	E	G	20.2500	4	P8GRF
I	F	H	J	G	19.7500	4	K
I	K	H	J	G	19.5000	4	P6GR
I	K	H	J	L	19.2500	4	P8GR
I	K	H	J	L	19.2500	4	GRF
I	K	H	J	L	19.2500	4	S15
I	K	M	J	L	19.0000	4	S5F
I	K	M	J	L	19.0000	4	S10F
I	K	M	J	L	19.0000	4	P6F
I	K	M	J	L	19.0000	4	S10
	K	M	J	L	18.7500	4	P6GRF
	K	M	J	L	18.5000	4	S5GRF
	K	M	J	L	18.5000	4	S10GR
	K	M	J	L	18.5000	4	GR
	K	M	J	L	18.5000	4	S5
	K	M		L	18.2500	4	S15GRF
	K	M		L	18.2500	4	S15F
		M		L	18.0000	4	S5GR
		M		L	18.0000	4	S10GRF
		M			17.7500	4	S15GR
			N		12.7500	4	L5
			N		12.5000	4	L5GR
			O		11.2500	4	L5GRF
			O		10.7500	4	L5F
			P		9.2500	4	L15
			P		9.2500	4	L10F
			P		9.0000	4	L10GR
			P		8.7500	4	L10
			P		8.5000	4	L10GRF
			Q		6.7500	4	L15F
	R		Q		6.0000	4	L15GRF
	R				5.2500	4	L15GR

Greenhouse Session 2: Total Carbon (%)

Duncan Grouping				Mean	N	treat
		A		3.8000	4	P8
		B		3.4500	4	P6
		C		2.5500	4	P4GRF
		C		2.5250	4	P4GR
		C		2.3500	4	P8F
		C		2.3250	4	P4
D		C		2.2250	4	P4F
D		E		2.0000	4	P8GR
F		E		1.8500	4	P8GRF
F		E		1.8250	4	P6GRF
F		E		1.8000	4	P6GR
F		G		1.6250	4	P6F
F		G		1.5250	4	P2
F		G		1.5250	4	P2F
H		G		1.3750	4	P2GR
H		G		1.3750	4	P2GRF
H		I		1.1750	4	S15F
H		I		1.1500	4	S15
H		I		1.1000	4	S15GR
H		I		1.1000	4	S15GRF
H		I	J	1.0500	4	S5GR
H	K	I	J	1.0250	4	S10F
H	K	I	J	1.0250	4	S10
H	K	I	J	1.0250	4	S10GR
	K	I	J	1.0000	4	S5GRF
	K	I	J	1.0000	4	S5F
	K	I	J	1.0000	4	F
	K	I	J	1.0000	4	GR
	K	I	J	0.9750	4	S5
	K	I	J	0.9750	4	K
	K	I	J	0.9750	4	GRF
	K	I	J	0.9750	4	S10GRF
	K	L	J	0.7000	4	L5GR
M	K	L		0.6750	4	L5
M		L	N	0.5250	4	L5GRF
M		L	N	0.5250	4	L5F
M		L	N	0.5000	4	L10GR
M		L	N	0.4750	4	L10F
M		L	N	0.4750	4	L10
M		L	N	0.4500	4	L10GRF
M		L	N	0.3500	4	L15
M			N	0.3250	4	L15GRF
M			N	0.3250	4	L15GR
			N	0.3000	4	L15F

Greenhouse Session 3: Available N (mg kg^{-1})

Duncan Grouping			Mean	N	treat
	A		305.75	4	AG4GR
	B		190.25	4	AG2
	B		182.75	4	AG4
C	B		136.75	4	hF
C	D		121.00	4	hFLS
C	D	E	94.50	4	AG2GR
F	D	E	69.25	4	lCLS
F	G	E	58.75	4	fFLS
F	G	E	52.00	4	hCLS
F	G	E	47.75	4	fCLS
F	G	E	45.50	4	hRLS
F	G	E	39.25	4	fRLS
F	G		28.50	4	hGLS
F	G		23.00	4	fGlRLS
F	G		19.75	4	lRLS
F	G		18.00	4	fCfGLS
F	G		15.00	4	fGLS
F	G		13.50	4	lF
F	G		12.50	4	fGhRLS
F	G		8.00	4	fClGLS
	G		5.50	4	hFP
	G		4.50	4	lC
	G		3.75	4	fChG
	G		2.75	4	hC
	G		2.50	4	lGLS
	G		2.25	4	hG
	G		2.00	4	K
	G		2.00	4	lFP
	G		1.75	4	hR
	G		1.75	4	lRP
	G		1.50	4	lG
	G		1.50	4	lCP
	G		1.25	4	fGlR
	G		1.25	4	fCP
	G		1.25	4	fClGP
	G		1.25	4	hGP
	G		1.00	4	hRP
	G		1.00	4	fGP
	G		1.00	4	fRP
	G		1.00	4	lR
	G		1.00	4	fGlRP
	G		1.00	4	hCP
	G		1.00	4	fGRhP
	G		1.00	4	PM2
	G		0.75	4	lGP
	G		0.75	4	fGhR
	G		0.75	4	fClG
	G		0.00	4	PM2GR
	G		0.00	4	PM4GR
	G		0.00	4	PM4

Greenhouse Session 3: Available P (mg kg^{-1})

Duncan Grouping				Mean	N	treat
		A		132.000	4	AG4GR
		B		109.500	4	hF
		B		109.250	4	hFLS
		B		98.500	4	AG4
		C		77.500	4	hFP
		D		60.250	4	fFLS
E		D		52.000	4	PM4GR
E		D	F	49.500	4	lF
E		D	F	47.250	4	AG2
E	G	D	F	44.750	4	AG2GR
E	G	H	F	38.500	4	PM2GR
I	G	H	F	33.500	4	PM4
I	G	H	J	29.000	4	lFP
I		H	J	24.500	4	PM2
I		H	J	23.500	4	hCLS
I			J	18.750	4	fCfGLS
I			J	17.250	4	lCLS
I			J	17.000	4	fCLS
I			J	16.750	4	fRLS
I			J	16.500	4	fChG
I			J	15.000	4	fGlRLS
I			J	15.000	4	hR
I			J	14.750	4	fGhRLS
I			J	14.750	4	hGLS
I			J	14.250	4	hRLS
I			J	13.500	4	hRP
I			J	13.250	4	fGLS
I			J	13.250	4	hC
I			J	13.250	4	fGhR
I			J	13.250	4	lR
I			J	13.250	4	lRLS
I			J	13.250	4	lC
			J	13.000	4	fClG
			J	13.000	4	fGRhP
			J	12.750	4	fCP
			J	12.500	4	fClGLS
			J	12.250	4	fRP
			J	12.250	4	hCP
			J	12.250	4	fGlR
			J	12.000	4	lGP
			J	11.500	4	hG
			J	11.500	4	lRP
			J	11.500	4	fGlRP
			J	11.500	4	fClGP
			J	11.000	4	K
			J	11.000	4	lCP
			J	11.000	4	lG
			J	10.750	4	hGP
			J	10.750	4	fGP
			J	9.750	4	lGLS

Greenhouse Session 3: Available K (mg kg^{-1})

Duncan Grouping		Mean	N	treat
	A	2987.50	4	AG4
	B	2672.50	4	AG4GR
	C	1962.50	4	AG2
	D	1762.50	4	AG2GR
	E	266.00	4	lGP
F	E	248.00	4	lR
F	E	234.75	4	lF
F	E	228.50	4	hF
F	E	225.50	4	hG
F	E	220.00	4	lG
F	E	219.25	4	K
F	E	215.50	4	lC
F	E	215.25	4	hR
F	E	212.50	4	fClG
F	E	209.00	4	hC
F	E	208.00	4	fChG
F	E	207.25	4	fGlRP
F	E	204.75	4	fGhR
F	E	204.50	4	fCP
F	E	202.75	4	fGRhP
F	E	202.50	4	fClGP
F	E	200.25	4	fGlR
F	E	197.75	4	lFP
F	E	195.50	4	lCP
F	E	192.00	4	fGP
F	E	190.00	4	lRP
F	E	188.25	4	hFP
F	E	187.75	4	hCP
F	E	179.25	4	hGP
F	E	177.75	4	PM2
F	E	176.75	4	hRP
F	E	176.25	4	fRP
F	E	172.50	4	hFLS
F	E	168.50	4	PM2GR
F	E	168.00	4	PM4GR
F	E	167.00	4	PM4
F	E	158.50	4	fFLS
F	E	147.50	4	fRLS
F	E	147.50	4	hGLS
F	E	138.25	4	fGlRLS
F	E	135.50	4	hCLS
F	E	134.50	4	fGhRLS
F	E	132.50	4	lRLS
F	E	130.50	4	fCfGLS
F	E	126.00	4	lCLS
F	E	125.75	4	fClGLS
F	E	125.50	4	fCLS
F	E	125.00	4	hRLS
F		102.75	4	fGLS
F		95.00	4	lGLS

Greenhouse Session 3: Available S (mg kg^{-1})

Duncan Grouping					Mean	N	treat
		A			1450.00	4	hG
		B			1187.50	4	lG
		B			1098.50	4	fGRhP
C		B			1042.00	4	fChG
C		D			904.00	4	lR
C		D	E		870.50	4	hR
		D	E		832.00	4	AG4GR
F		D	E		807.00	4	fGhRLS
F		D	E		802.00	4	hF
F		D	E		801.50	4	fGhR
F		D	E		787.00	4	lC
F	G	D	E		767.50	4	K
F	G	D	E		750.00	4	fGlR
F	G	D	E		727.50	4	hGLS
F	G	D	E		712.00	4	hGP
F	G	D	E		707.50	4	lF
F	G	D	E		705.00	4	fGlRP
F	G	D	E		702.50	4	AG2GR
F	G	D	E		699.50	4	AG2
F	G	D	E		699.00	4	fClGP
F	G	D	E		687.00	4	hC
F	G	H	E		655.50	4	lGP
F	G	H	I		593.00	4	fClG
J	G	H	I		565.00	4	fGlRLS
J	G	H	I		562.00	4	fCfGLS
J	K	H	I		473.00	4	AG4
J	K	H	I		467.50	4	hFLS
J	K	H	I		455.50	4	fCP
J	K	H	I		446.00	4	PM4GR
J	K		I		419.50	4	fGP
J	K		I		409.00	4	lFP
J	K	L	I		398.50	4	fRP
J	K	L	I		398.00	4	fGLS
J	K	L			367.50	4	hRLS
J	K	L	M		359.25	4	PM2
J	K	L	M		355.00	4	lRLS
J	K	L	M		350.00	4	fClGLS
J	K	L	M		345.00	4	lCP
N	K	L	M		311.50	4	PM4
O N	K	L	M		296.25	4	hFP
O N	K	L	M	P	276.75	4	lGLS
O N	K	L	M	P	256.75	4	lRP
O N		L	M	P	186.00	4	PM2GR
O N			M	P	143.50	4	fRLS
O N				P	110.75	4	hRP
O N				P	102.00	4	fFLS
O				P	96.25	4	hCP
				P	68.75	4	hCLS
				P	64.75	4	lCLS
				P	61.00	4	fCLS

Greenhouse Session 3: CEC (meq 100 g^{-1})

Duncan Grouping							Mean	N	treat
			A				24.5000	4	hFP
	B		A				23.5000	4	AG4GR
	B		A		C		23.0000	4	lF
	B		A		C		23.0000	4	lCP
	B		A		C		23.0000	4	fRP
	B	D	A		C		22.7500	4	fGlRP
	B	D	A		C		22.7500	4	fCP
E	B	D	A		C		22.5000	4	lFP
E	B	D	A		C		22.5000	4	lGP
E	B	D	F		C		22.0000	4	hCP
E	B	D	F		C	G	21.7500	4	AG4
E	B	D	F		C	G	21.7500	4	fGP
E	B	D	F	H	C	G	21.5000	4	lC
E	B	D	F	H	C	G	21.5000	4	fGRhP
E	B	D	F	H	C	G	21.5000	4	hC
E	B	D	F	H	C	G	21.5000	4	hRP
E	B	D	F	H	C	G	21.2500	4	PM2
E		D	F	H	C	G	20.7500	4	lRP
E		D	F	H	C	G	20.7500	4	fGhR
E		D	F	H	C	G	20.7500	4	fClGP
E		D	F	H	C	G	20.7500	4	PM4GR
E		D	F	H	C	G	20.7500	4	hF
E		D	F	H		G	20.5000	4	hG
E			F	H		G	20.2500	4	fGlR
			F	H		G	20.0000	4	fClG
			F	H		G	20.0000	4	PM4
			F	H		G	20.0000	4	fChG
			F	H		G	20.0000	4	hGP
			F	H		G	19.7500	4	lG
			F	H		G	19.7500	4	PM2GR
				H		G	19.5000	4	AG2GR
				H		G	19.5000	4	K
				H		G	19.5000	4	hR
				H			19.2500	4	lR
				H			19.2500	4	AG2
			I				14.5000	4	hGLS
	J		I				14.2500	4	fFLS
	J		I				13.7500	4	fRLS
	J		I				13.7500	4	fClGLS
	J		I				13.5000	4	hFLS
	J		I				13.5000	4	lRLS
	J		I				13.5000	4	hCLS
	J		I		K		13.0000	4	lCLS
	J		I		K		12.7500	4	hRLS
	J		I		K		12.2500	4	fCLS
	J				K		12.0000	4	fGlRLS
			L		K		11.2500	4	fCfGLS
			L		K		11.0000	4	fGhRLS
	M		L				9.2500	4	lGLS
	M						8.7500	4	fGLS

Greenhouse Session 3: Total Carbon (%)

Duncan Grouping				Mean	N	treat
		A		3.8000	4	AG4GR
		B		3.4250	4	AG4
		C		2.3500	4	lCP
D		C		2.1750	4	PM4GR
D		C	E	2.1500	4	hFP
D	F	C	E	2.1000	4	fRP
D	F		E	2.0250	4	AG2
D	F		E	2.0250	4	fGRhP
D	F	G	E	1.9250	4	fGlRP
D	F	G	E	1.9250	4	lGP
D	F	G	E	1.9000	4	hCP
D	F	G	E	1.8750	4	hRP
D	F	G	E	1.8500	4	AG2GR
D	F	G	E	1.8500	4	lFP
	F	G	E	1.8250	4	fClGP
	F	G	E	1.8250	4	PM4
H	F	G		1.7750	4	fGP
H		G	I	1.6250	4	hGP
H		J	I	1.5000	4	lRP
		J	I	1.4250	4	fCP
		J	I	1.4000	4	PM2GR
K		J		1.2250	4	PM2
K		L		1.0000	4	fGlR
K		L	M	0.9750	4	fClG
K		L	M	0.9750	4	fChG
K		L	M	0.9500	4	lC
K		L	M	0.9500	4	lF
K		L	M	0.9500	4	hF
K	N	L	M	0.9250	4	hC
K	N	L	M	0.9250	4	hG
K	N	L	M	0.9250	4	fGhR
K	N	L	M	0.9250	4	lR
K	N	L	M	0.9250	4	lG
K	N	L	M	0.9000	4	hR
K	N	L	M	0.9000	4	K
O	N	L	M	0.7000	4	hGLS
O	N		M	0.6500	4	lCLS
O	N			0.6000	4	hRLS
O	N			0.6000	4	fRLS
O	N			0.6000	4	lRLS
O				0.5500	4	hFLS
O				0.5500	4	fCfGLS
O				0.5500	4	fFLS
O				0.5250	4	fClGLS
O				0.5250	4	hCLS
O				0.4750	4	fGhRLS
O				0.4750	4	fCLS
O				0.4500	4	fGlRLS
O				0.4250	4	lGLS
O				0.4250	4	fGLS

Field Season 2: Available N (mg kg^{-1})

Duncan Grouping	Mean	N	treat
A	54.13	3	PSRG20-30
A	44.87	3	PSRG10-20
B	14.27	3	PSRG0-10
B	3.40	3	Ca20-30
B	2.27	3	Ca10-20
B	1.80	3	G20-30
B	1.80	3	PGCa0-10
B	1.67	3	Ca0-10
B	1.67	3	L0-10
B	1.53	3	PGCa20-3
B	1.33	3	PGCa10-2
B	1.33	3	G10-20
B	1.20	3	R20-30
B	1.20	3	PG20-30
B	1.13	3	G0-10
B	1.00	3	PG10-20
B	0.93	3	PG0-10
B	0.93	3	LGR0-10
B	0.93	3	R0-10
B	0.87	3	R10-20
B	0.87	3	LGR20-30
B	0.80	3	L20-30
B	0.80	3	L10-20
B	0.73	3	LGR10-20

Field Season 2: Available P (mg kg^{-1})

Duncan Grouping	Mean	N	treat
A	140.67	3	PSRG0-10
B	77.00	3	PSRG20-3
C	38.67	3	PSRG10-2
C	28.67	3	Ca0-10
C	28.00	3	G0-10
C	27.00	3	PG0-10
C	26.67	3	PGCa0-10
C	20.33	3	L0-10
C	19.67	3	R0-10
C	19.00	3	LGR0-10
C	12.00	3	L10-20
C	11.33	3	PGCa10-2
C	10.33	3	LGR10-20
C	10.00	3	PGCa20-3
C	10.00	3	Ca20-30
C	10.00	3	G10-20
C	9.67	3	PG10-20
C	9.33	3	PG20-30
C	9.00	3	Ca10-20
C	8.67	3	L20-30
C	8.33	3	R10-20
C	8.00	3	LGR20-30
C	8.00	3	R20-30
C	7.67	3	G20-30

Field Season 2: Available K (mg kg^{-1})

Duncan Grouping					Mean	N	treat
			A		219.00	3	PG10-20
	B		A		212.67	3	Ca10-20
	B		A	C	209.33	3	PG20-30
	B	D	A	C	204.67	3	G10-20
E	B	D	A	C	197.67	3	Ca20-30
E	B	D	A	C	195.00	3	PSRG20-3
E	B	D	A	C	192.67	3	PSRG0-10
E	B	D	A	C	192.33	3	PG0-10
E	B	D	A	C	185.67	3	PGCa10-2
E	B	D	A	C	185.33	3	G20-30
E	B	D	A	C	185.00	3	Ca0-10
E	B	D	A	C	181.33	3	R0-10
E	B	D	A	C	175.67	3	PGCa20-3
E	B	D	A	C	171.33	3	PGCa0-10
E	B	D	A	C	171.00	3	G0-10
E	B	D	A	C	170.00	3	PSRG10-2
E	B	D	A	C	165.67	3	L20-30
E	B	D	A	C	157.33	3	R10-20
E	B	D		C	155.67	3	R20-30
E		D		C	149.33	3	LGR20-30
E		D		C	147.33	3	L0-10
E		D			144.67	3	L10-20
E		D			143.67	3	LGR0-10
E					136.67	3	LGR10-20

Field Season 2: Available S ($mg\ kg^{-1}$)

Duncan Grouping				Mean	N	treat
		A		1129.3	3	PG10-20
B		A		1001.3	3	PG20-30
B		A	C	906.0	3	LGR10-20
B		A	C	904.0	3	PSRG0-10
B		A	C	900.7	3	PGCa20-3
B		A	C	898.7	3	PGCa10-2
B		A	C	848.7	3	PSRG20-3
B		A	C	827.3	3	LGR0-10
B		A	C	822.0	3	PSRG10-2
B		A	C	808.0	3	PGCa0-10
B	D	A	C	774.7	3	L10-20
B	D	A	C	764.7	3	L20-30
B	D	A	C	754.0	3	L0-10
B	D	A	C	712.0	3	LGR20-30
B	D	A	C	694.0	3	PG0-10
B	D	A	C	647.3	3	G20-30
B	D		C	513.0	3	Ca10-20
B	D		C	508.7	3	R0-10
B	D		C	480.7	3	G10-20
B	D		C	432.0	3	R20-30
	D		C	414.3	3	Ca20-30
	D		C	361.0	3	R10-20
	D		C	322.0	3	G0-10
	D			215.0	3	Ca0-10

Field Season 2: CEC (meq 100 g^{-1})

Duncan Grouping							Mean	N	treat
			A				23.367	3	PG10-20
	B		A				22.700	3	PSRG20-3
	B		A		C		21.867	3	PGCa10-2
	B	D	A		C		20.600	3	PG20-30
E	B	D	A		C		18.433	3	PSRG10-2
E	B	D	A		C		18.400	3	PGCa20-3
E	B	D	A		C	F	18.067	3	Ca10-20
E	B	D	A		C	F	17.100	3	G10-20
E	B	D	A		C	F	17.100	3	PG0-10
E	B	D	A	G	C	F	16.800	3	Ca20-30
E	B	D	A	G	C	F	16.600	3	PGCa0-10
E	B	D	A	G	C	F	15.967	3	G20-30
E	B	D	A	G	C	F	15.867	3	Ca0-10
E	B	D		G	C	F	15.233	3	R0-10
E	B	D		G	C	F	15.100	3	G0-10
E		D		G	C	F	14.700	3	PSRG0-10
E		D		G		F	13.700	3	R20-30
E		D		G		F	13.667	3	L20-30
E		D		G		F	13.600	3	R10-20
E				G		F	12.433	3	L0-10
E				G		F	12.000	3	LGR0-10
E				G		F	11.867	3	LGR20-30
				G		F	10.433	3	L10-20
				G			9.133	3	LGR10-20

Field Season 2: Total Carbon (%)

Duncan Grouping		Mean	N	treat
	A	2.4333	3	PG10-20
	A	2.4000	3	PGCa10-2
B	A	2.2000	3	PSRG20-3
B	A	2.1333	3	PSRG10-2
B	A	1.9333	3	PG20-30
B	A	1.7667	3	PGCa20-3
B	C	1.5667	3	PSRG0-10
B	C	1.5333	3	PGCa0-10
B	C	1.5333	3	PG0-10
D	C	0.9667	3	Ca10-20
D	C	0.8667	3	Ca0-10
D	C	0.8667	3	G10-20
D	C	0.8667	3	G20-30
D	C	0.8333	3	G0-10
D	C	0.8333	3	Ca20-30
D		0.7333	3	R0-10
D		0.7000	3	R10-20
D		0.7000	3	R20-30
D		0.7000	3	L20-30
D		0.6333	3	LGR20-30
D		0.6000	3	L0-10
D		0.6000	3	LGR0-10
D		0.5333	3	L10-20
D		0.4000	3	LGR10-20